

**CHARACTERIZATION TEST REPORT FOR THE
MNEMONICS-UCF WIRELESS SURFACE ACOUSTIC
WAVE SENSOR SYSTEM**

TRANSDUCER DEVELOPMENT LABORATORY

FEBRUARY 28, 2013

ENGINEERING AND TECHNOLOGY DIRECTORATE

National Aeronautics and
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Prepared by:

Joshua J. Duncan, ESC-28
ESC Engineer

Concurrence:

Robert C. Smith, Jr., ESC-28
ESC Engineer

Approved by:

N. N. "Mike" Blalock, ESC-48
ESC Transducer Lab Lead

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ABBREVIATIONS, ACRONYMS, AND SYMBOLS

<i>Term</i>	<i>Definition</i>
A	ampere
ABS	acrylonitrile butadiene styrene
AC	alternating current
ADC	analog-to-digital converter
ASR&D	Applied Sensor Research & Development Corporation
AVO	Avoid Verbal Orders
°C	degrees Celsius
dB	decibel
dB μ V	decibels referenced to one microvolt
DIP	dual in-line package
DC	direct current
ECN	equipment control number
EDL	Engineering Development Laboratory
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EML	Electromagnetic Effects Laboratory
ESC	Engineering Services Contract
FCC	Federal Communications Commission
FFT	Fast Fourier Transform
FS	full scale
GB	gigabytes
GCF	gas correction factor
GHz	gigahertz
GPIB	General Purpose Interface Bus
GS/s	gigasamples per second
GSM	Global System for Mobile Communications
GUI	graphical user interface
H ₂ or H ₂	hydrogen

HDPE	high-density polyethylene
HP-IB	Hewlett-Packard Interface Bus
hr	hour
HVAC	heating, ventilating, and air conditioning
Hz	hertz
IC	integrated circuit
IEEE	Institute of Electrical and Electronics Engineers
ISM	industrial, scientific and medical
kHz	kilohertz
KSC	John F. Kennedy Space Center
LED	light-emitting diode
LN2	liquid nitrogen
m	meter
MEK	methyl ethyl ketone
MHz	megahertz
min	minute
MNI	Mnemonics, Inc.
MSL	Materials Science Laboratory
MSFC	George C. Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
ns	nanosecond
PCMCIA	Personal Computer Memory Card International Association
ppm	parts per million
PSD	power spectral density
PVC	polyvinyl chloride
RAM	random-access memory
RBW	resolution bandwidth
RF	radio frequency
RFA	Radio Frequency Authorization
S/N	serial number
SAW	surface acoustic wave

SBIR	Small Business Innovation Research
SCCM	standard cubic centimeters per minute
SLPM	standard liters per minute
STTR	Small Business Technology Transfer
TC	technical contact
TDL	Transducer Development Laboratory
UCF	University of Central Florida
V	volt
VBW	video bandwidth
WAC	Work Authorization Control
σ	standard deviation
"	inch

CHARACTERIZATION TEST REPORT FOR THE MNEMONICS-UCF WIRELESS SURFACE ACOUSTIC WAVE SENSOR SYSTEM

1. INTRODUCTION

1.1 Purpose

NASA's Kennedy Space Center (KSC) recently acquired two state-of-the-art wireless sensor systems as the final deliverable of a Phase II Small Business Technology Transfer (STTR) contract with Mnemonics, Inc. and the University of Central Florida (UCF), contract number NNX09CB69C. Mnemonics constructed the radio frequency (RF) interrogator portion of these systems and UCF constructed the sensors, which are based on a novel surface acoustic wave (SAW) architecture. The purpose of this testing is to characterize the performance of the system, both in its basic parameters and under a range of operating conditions.

1.2 Scope

NASA-funded development of SAW sensor technology is ongoing under a number of other STTR and Small Business Innovation Research (SBIR) contracts. The scope of this testing includes the sensor systems delivered to KSC under the above-referenced contract: two interrogator (transceiver) systems, Mnemonics part number 990-1139-001; four temperature sensors, with wooden mounting blocks; two antennas; two power supplies; network cables; and analysis software. Also included are a number of additional temperature sensors and newly-developed hydrogen sensors procured directly from UCF by KSC. One of the two interrogator systems was loaned to UCF to support their production of these additional sensors; thus the testing herein was primarily conducted with interrogator serial number 1, NASA ECN 2295445.

1.3 Reference Documents

The following documents form a part of this document to the extent specified herein.

KNPR 8715.3	KSC Safety Practices Procedural Requirements
TDL-0512	Transducers Labs Laboratory Safety Manual
TDL-0516	Transducer Development Laboratory Standard Cryogenic Operations and Test Set Up Reference Guide
TDL-0674-REF	Characterization Test Procedure for Surface Acoustic Wave (SAW) Hydrogen Sensors
Email dated 7 September 2011	KSC 110009 – Conditional Radio Frequency Authorization for the SAW RFID Interrogator

1.4 Data Handling

During testing, data was recorded by the test engineer on the data sheets included in the test procedure and in data log files. The data gathered during testing can be found in Appendix B.

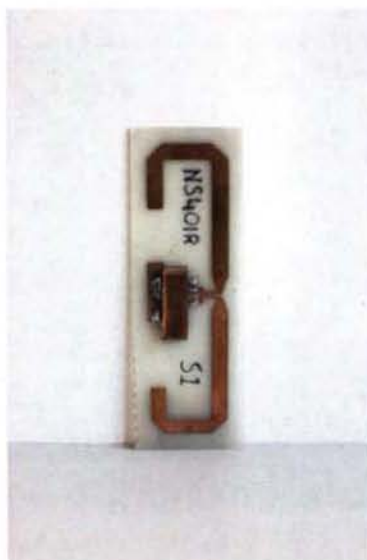
2. TEST PROCEDURES AND ANALYSIS

2.1 Objectives

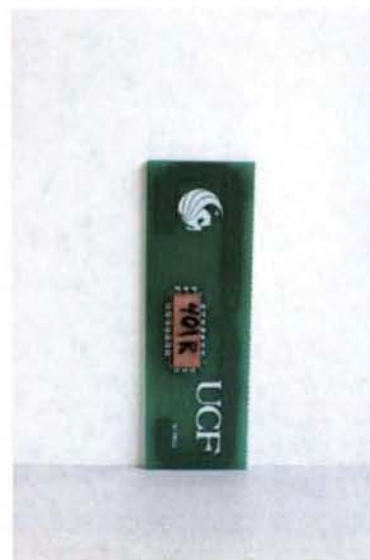
The objective of the testing herein is to characterize the electromagnetic compatibility (EMC) of the interrogator devices and quantify the performance of the sensor system as it is used to measure temperature and hydrogen concentration in various configurations.

2.2 Basic Characteristics

The SAW sensors (see Figure 1) are an assembly mounted on an FR-4 printed circuit board substrate, on which a folded dipole antenna pattern is laid out in copper. The sensor package, of similar size and shape to a dual in-line package (DIP) integrated circuit (IC), contains a lithium niobate (LiNbO_3) crystal which supports the SAW structures. The packaging design of the hydrogen sensors is similar to that of the temperature sensors; however, the hydrogen sensor package has an array of small holes to allow the sensor chip to be exposed to ambient hydrogen, while the temperature sensors have a solid cover.



Supplied temperature sensor



Newly procured temperature sensor

Figure 1. SAW temperature sensors

The SAW interrogator box (Figure 2) is a bench-top metal enclosure approximately 10 inches high by 4 inches tall by 8 inches deep. On one face of the box are three LED indicators: a green LED at the top lights solid when the power is on; a green LED in the center blinks when the system is operating correctly; and a red LED at the bottom indicates a fault. A momentary pushbutton resets the unit. There are also three electrical connections: an RJ45 is the primary Ethernet interface; a DB9 and an RJ11 are not documented and were not used in this testing. On the other face of the box are the vent for the cooling fan and four connections: a coaxial (barrel) connector for DC power; a female SMA connector for connecting the antenna; another female SMA connector used for Mnemonics' internal testing, not used here; and a pin-type connection (with ground lug) used as a trigger output. The supplied temperature measurement software runs in MATLAB with the Signal Processing Toolbox. For the temperature testing, a laboratory-assigned Dell Latitude E6500 with an Intel Core 2 Duo T9400 (2.53 GHz) processor and 2 GB of RAM with Windows XP Professional 32-bit was used to run the software. The hydrogen measurement software, procured from UCF along with the hydrogen sensors, is a compiled MATLAB application, and runs in the MATLAB Compiler Runtime environment. For the hydrogen testing, a laboratory-assigned Hewlett-Packard ProBook 6560b with an Intel Core i5-2520M (2.50 GHz) processor and 4 GB of RAM with Windows 7 Enterprise 64-bit was used to run the software.



Front view



Back view

Figure 2. RF interrogator box

When queried by the software, the interrogator sends out a stepped-frequency RF burst approximately 700 ns long, with 80 MHz of bandwidth centered at 915 MHz, having a nominal power of 3 W. This RF burst is received by the antenna on the sensor substrate, and a transducer excites a surface acoustic wave in the sensor crystal. This wave is reflected by a series of gratings called chips, and the reflected wave is converted back to an RF signal by the transducer. The RF signal is broadcast through the sensor antenna back to the interrogator antenna. The interrogator receives the RF signal from the sensor and mixes it down to a lower frequency, where it is digitized by a high-speed analog-to-digital converter (ADC). This data is transmitted over the Ethernet connection to the computer, which performs all the processing and analysis of the received signal to extract measurement data. The temperature sensors have one set of reflector chips, and the shift in reflected frequency is proportional to the temperature. The

hydrogen sensors have two sets of reflector chips; in the propagation path of one reflector is a hydrogen-sensitive film, which reduces the amplitude of the wave propagating in this path when exposed to hydrogen. The difference in amplitude between the two reflectors is given as an indication of hydrogen concentration. The shift in reflected frequency indicates the temperature, as with the temperature sensors; however, this capability shows significant offsets at room temperature, and was not tested further herein.

2.3 RF Characterization

Per the conditional KSC Radio Frequency Authorization (RFA) 110009, emissions characterization of the SAW interrogator was required before the system could be used outside the EMI test chamber. A simple test setup was constructed inside the chamber for this characterization. The interrogator itself was placed outside the chamber for easier access, and the antenna connection was routed through a type N bulkhead feedthrough on the chamber wall. The antenna was placed on the copper-surfaced test table inside the chamber, and one meter away was placed an ETS-Lindgren 3115 Double-Ridged Guide Antenna to receive the signal (see Figure 3). Two different pieces of test equipment were used to characterize the signal in this configuration: a high-speed digital oscilloscope, and a spectrum analyzer. In addition, near-field probe testing was conducted, using an EMC analyzer (specialized spectrum analyzer) to process the received signal.



Figure 3. RF characterization test setup

Initial testing revealed difficulties in capturing the interrogator output on a spectrum analyzer. The output signal is nominally a stepped-frequency sine wave burst, 700 ns long, centered at 915 MHz, generated once per query by the operating software. The supplied version of the

operating software generated queries approximately once every ten seconds. Experimentation showed that the trigger signal output by the interrogator would be received after the start of the RF pulse, making it impossible to pre-trigger a spectrum analyzer using the provided trigger signal. Additionally, none of the available spectrum analyzers (see Table 1) had the capability to do a single-shot characterization of an RF pulse; all were of the swept-frequency type. An attempt to use the ETS-Lindgren FM5004 Field Monitor with an Amplifier Research FP2000 Isotropic Field Probe (see Table 2) gave no observable field measurement, likely because the effective duty cycle of the RF signal was so low.

Table 1. Available spectrum analyzers (as of 7 December 2011)

<i>Spectrum Analyzer</i>	<i>Frequency Range</i>
IFR Systems ¹ 2390A Spectrum Analyzer	9 kHz to 22 GHz
Agilent E7405A EMC Analyzer	100 Hz to 26.5 GHz
Hewlett-Packard ² 8568A Spectrum Analyzer	100 Hz to 1.5 GHz
Agilent E4440A PSA Series Spectrum Analyzer	3 Hz to 26.5 GHz

Table 2. Available field probes (as of 12 December 2011)

<i>Field Probe</i>	<i>Frequency Range</i>
Amplifier Research FP2000 Isotropic Field Probe	10 kHz to 1000 MHz
Amplifier Research FP2080 Isotropic Field Probe	80 MHz to 40 GHz
ETS-Lindgren HI-4422 Isotropic Electric Field Probe	10 kHz to 1000 MHz
ETS-Lindgren HI-6053 Isotropic Electric Field Probe	10 MHz to 40 GHz

2.3.1 Oscilloscope

Test Method

Given the limitations of the available spectrum analyzers, a Tektronix TDS5104B high-speed digital oscilloscope (see Table 3) was used to capture the received signal directly. The oscilloscope could be triggered on the rising edge of the RF signal, and has sufficient bandwidth and memory to capture the full length of the RF burst.

Table 3. Tektronix TDS5104B characteristics

Analog bandwidth	1 GHz
Maximum sample rate	5 GS/s
Metrology number	M88708
Calibrated	2 Sep 2011
Calibration due	2 Mar 2012
Testing performed	12-14 Sep 2011

¹ IFR Systems is now part of Aeroflex.

² Hewlett-Packard's test equipment business is now part of Agilent Technologies.

The oscilloscope was connected to the antenna directly via a coaxial cable, fed out of the EMI chamber using a bulkhead feedthrough. The trigger level was set above the ambient noise level, and configured for a single acquisition. This allowed the capture of the pulse in the time domain. In addition, the oscilloscope has a built-in FFT feature, which displays the calculated spectrum of the captured data. Multiple window (internal processing filter) types are available; two were used here: Gaussian and rectangular. Since the calculated spectrum was observed to vary somewhat from pulse to pulse, the oscilloscope was set to repetitive trigger, and the "infinite persistence" feature was used to overlay a series of spectra, giving an average envelope of the frequency content of the pulses.

Data, Observations, and Analysis

Figure 4 and Figure 5 show the leading and trailing edges, respectively, of the RF pulse as captured by the oscilloscope. Figure 6 gives the amplitude envelope of the pulse, using the local minima and maxima of the data. Note that this data is interpolated on the oscilloscope, improving the displayed resolution of the waveform but not the actual sampling rate; note also that the oscilloscope data has not been corrected for the effects of the antenna and cabling.

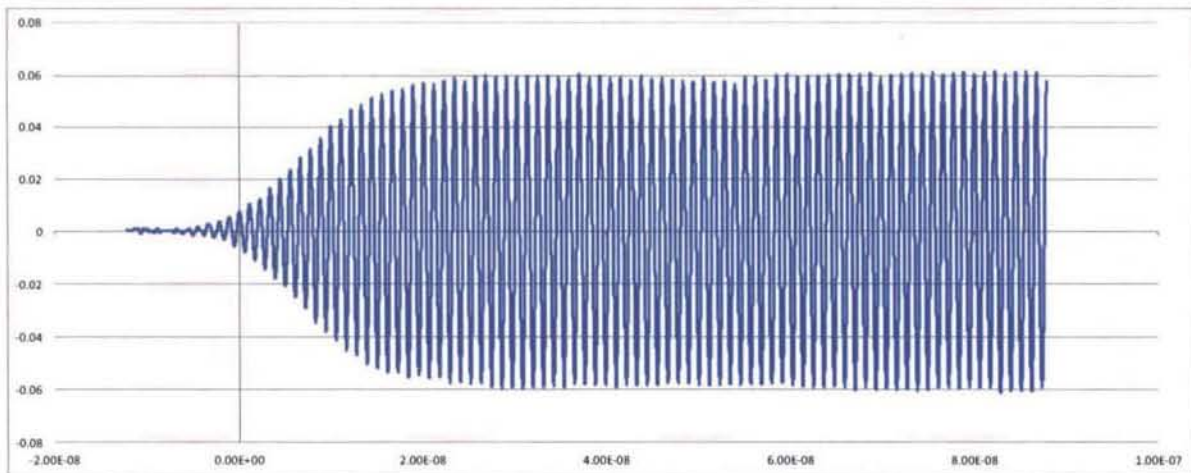


Figure 4. Leading edge of RF pulse

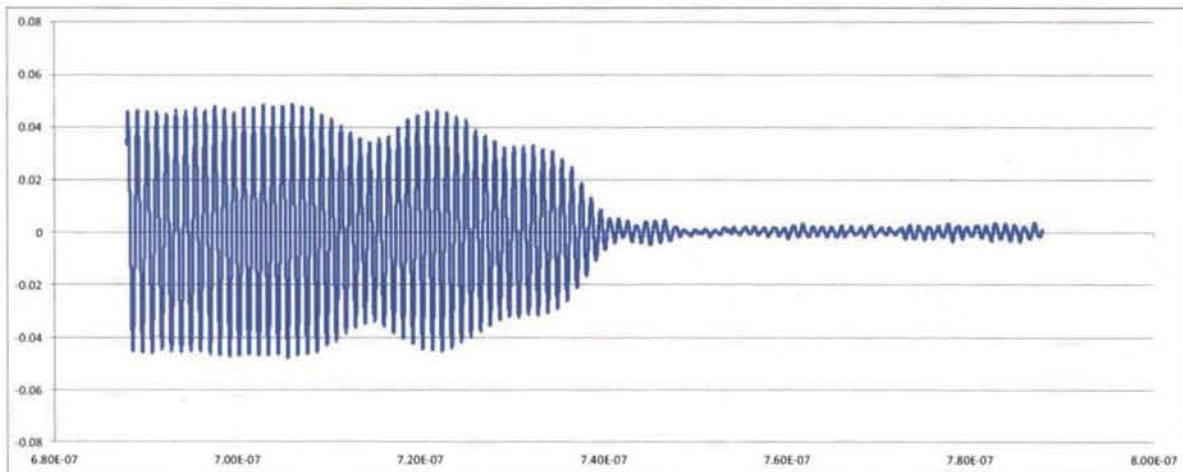


Figure 5. Trailing edge of RF pulse

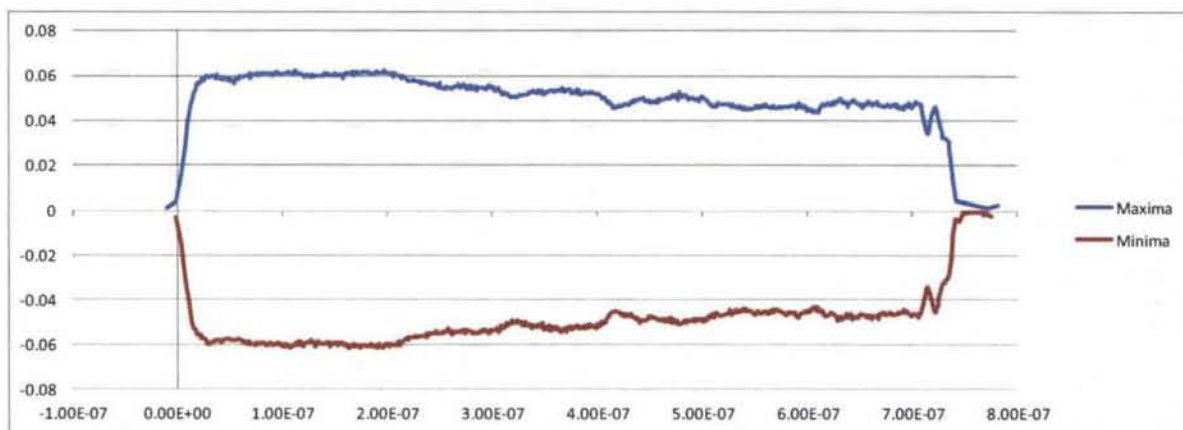


Figure 6. Amplitude envelope of RF pulse

Figure 7 shows the overlaid spectra of approximately 100 pulses, processed using the FFT with a Gaussian window, showing a peak approximately 50 dB above the background noise level. Figure 8 shows a similar capture, processed using a rectangular window; this shows a peak roughly 47 dB above the background noise level.

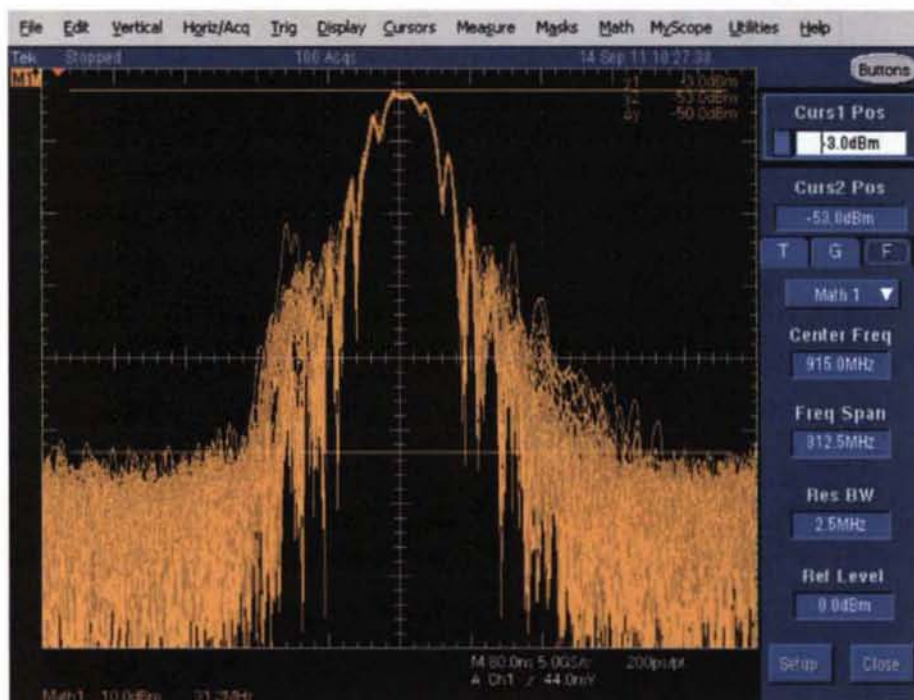


Figure 7. Oscilloscope FFT, Gaussian window (approximately 100 pulses)

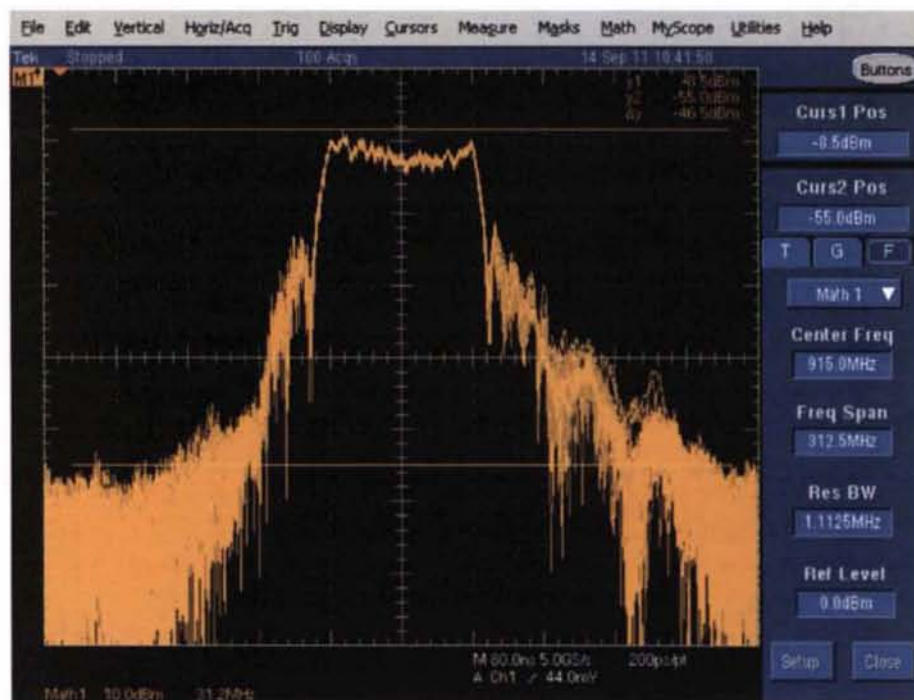


Figure 8. Oscilloscope FFT, rectangular window (approximately 100 pulses)

2.3.2 Spectrum Analysis

Although the oscilloscope captures provide a thorough characterization of the fundamental pulse spectrum, the available analog bandwidth is 1 GHz, which does not allow the analysis of harmonics. Because the harmonics are critical to understanding the electromagnetic compatibility of the device, an alternate approach was developed, to use a spectrum analyzer in "max hold" mode (record the maximum observed value for a given period of time), and a long sample time to capture as many pulses as possible. The spectrum analyzer used for this testing was the Agilent E4440A; see Table 4 for details. Also in the signal path were the components listed in Table 5. These components were well-characterized for use in EMI pre-qualification testing in the laboratory, and their available correction factors were used to scale the data to the estimated electric field at the antenna position.

Table 4. Agilent E4440A characteristics

Bandwidth	3 Hz to 26.5 GHz
Options	111 USB Interface 115 Compact Flash Memory 239 EMC Analysis Application
Metrology number	M89632
Calibrated	14 Jul 2011
Calibration due	14 Jul 2012
Testing performed	14-22 Sep 2011

Table 5. Additional spectrum analysis components

ETS-Lindgren 3115 Double-Ridged Guide Antenna
Agilent 87405C Preamplifier
Aeroflex/Weinschel attenuator
Cables

As a background reference, the spectrum analyzer was used to capture the spectrum of the EMI chamber with no operating devices inside. The captured spectrum for two hours, up to 3 GHz, is shown in Figure 9. Note two peaks in the background noise, which are thought to be RF signals impinging directly on the spectrum analyzer outside the chamber. The spectrum up to 5 GHz (Figure 10) shows similar interference peaks.



SCREEN10.GIF

Run time: 2 hr

Figure 9. Spectrum of quiet EMI chamber to 3 GHz (raw data)³

³ Note that the assumption that the left peak is GSM-850 cell phone interference is supported by the narrowband spectrum corresponding to specific GSM uplink channels. Three closely spaced peaks are observable in the raw data: 826.5 MHz, close to GSM channels 139 and 140; 835.4 MHz, GSM channel 184; and 844.4 MHz, GSM channel 229.

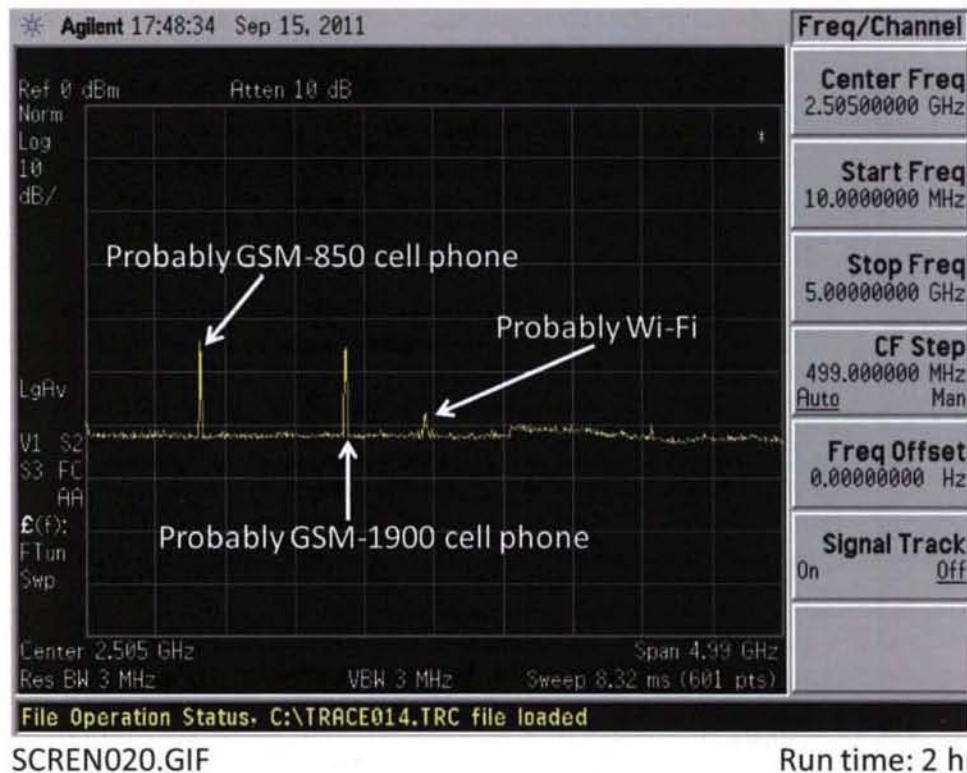


Figure 10. Spectrum of quiet EMI chamber to 5 GHz (raw data)⁴

2.3.2.1 Existing Software

Test Method

Using the existing UCF/Mnemonics software, the interrogator system was operated for approximately two hours with no sensors in the chamber, so that the output spectrum could be captured without influence from the sensors.

Data, Observations, and Analysis

The output spectrum of the interrogator up to 3 GHz, captured with the existing software, is shown in Figure 11. Note the small gaps in the spectrum of each harmonic, which indicates the sweep of the spectrum analyzer never captured a pulse in that frequency band. The small peak to the left of the third harmonic is thought to be IEEE 802.11b/g “Wi-Fi” (or another interference source in the ISM band). The output spectrum up to 5 GHz is shown in Figure 12; some peaks are visible in the fourth harmonic frequency band, but there are significant gaps in the spectra.

⁴ Note that the assumption that the left two peaks are GSM cell phone interference is supported by the narrowband spectrum corresponding to specific GSM uplink channels. The peaks observable in the raw data are the following: 833.4 MHz, GSM channel 174; and 1872.9 MHz, close to GSM channels 625 and 626.

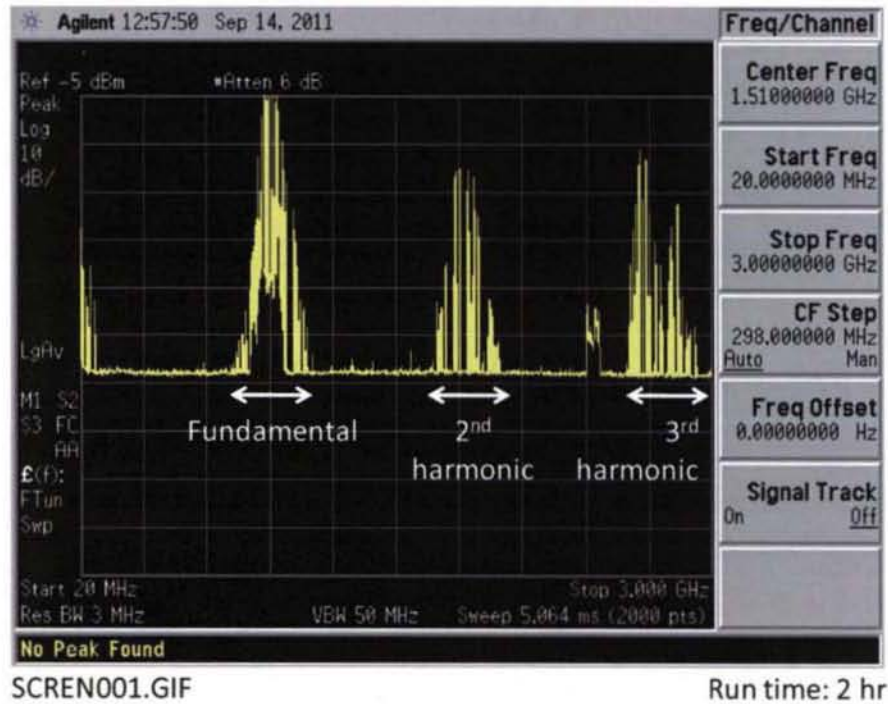


Figure 11. Spectrum of interrogator to 3 GHz using existing software (raw data)

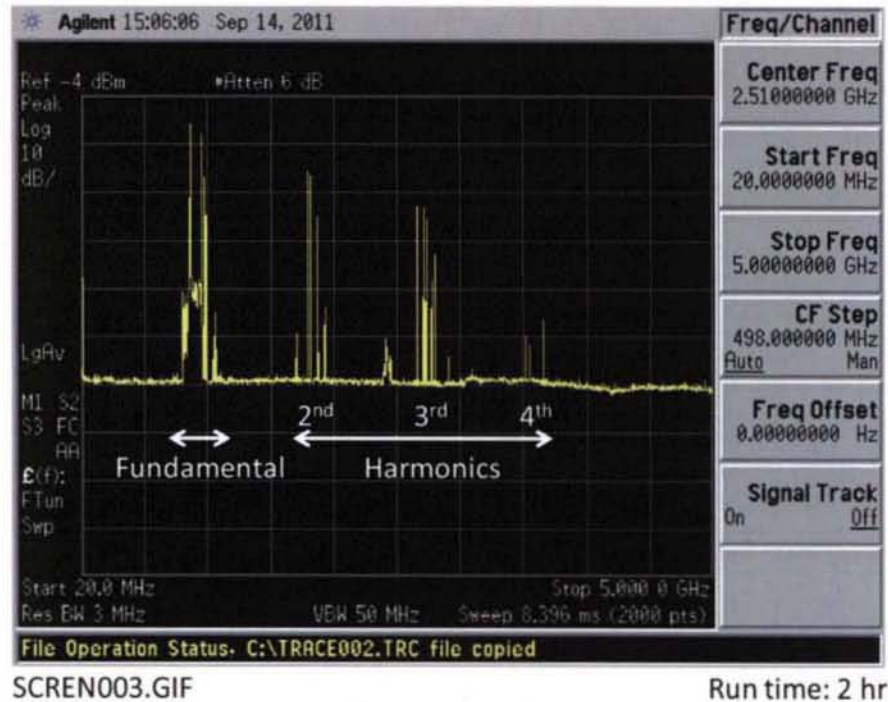


Figure 12. Spectrum of interrogator to 5 GHz using existing software (raw data)

2.3.2.2 Rapid Query Software

Test Method

Because the intermittent nature of the query signal leads to incomplete spectrum profiles, a MATLAB script was written to query the sensors more often, typically close to 8 times per second, without analyzing the received data; in the supplied software, the data analysis takes the vast majority of each query period. Using this script, more detailed spectra can be captured, since a given sweep of the spectrum analyzer has a greater chance of receiving an RF pulse.

Data, Observations, and Analysis

The following plots show the spectra captured using the rapid query script; each shows the full extent of the captured spectrum data. These plots have been corrected for the losses and gains in the RF path, as well as the antenna factor, to give a calculated value of the electric field at the receiving antenna. Figure 13 shows the interrogator spectrum out to 5 GHz; note that some peaks are visible as far out as the fifth harmonic. The noise floor curves upward with increasing frequency, primarily due to the characteristics of the cables and the antenna. Figure 14 shows a much narrower capture of the fundamental frequency band; data is not shown all the way to the left side (715 MHz) because those frequencies lie outside the antenna's design range. The upper blue trace is the spectrum when the interrogator is transmitting; the lower red trace is the spectrum when the interrogator is powered but idle (not transmitting). Note that the shape of the spectral profile compares well to that captured on the oscilloscope with the rectangular-window FFT (Figure 8). The peak value of the electric field in the fundamental band is 134 dB μ V/m. Figure 15 shows the second harmonic spectrum, with a peak value of 114 dB μ V/m, or about 20 dB below the fundamental. Figure 16 shows the third harmonic spectrum, with a peak value of 109 dB μ V/m, or about 25 dB below the fundamental. The fourth harmonic spectrum is shown in Figure 17, with a peak value of 92 dB μ V/m, or about 42 dB below the fundamental.

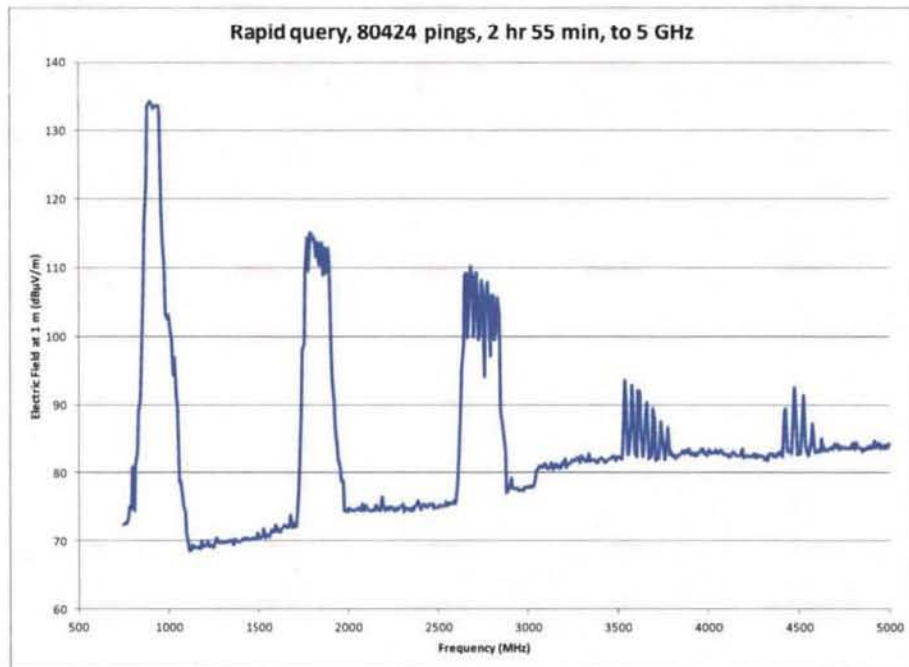


Figure 13. Rapid query spectrum to 5 GHz

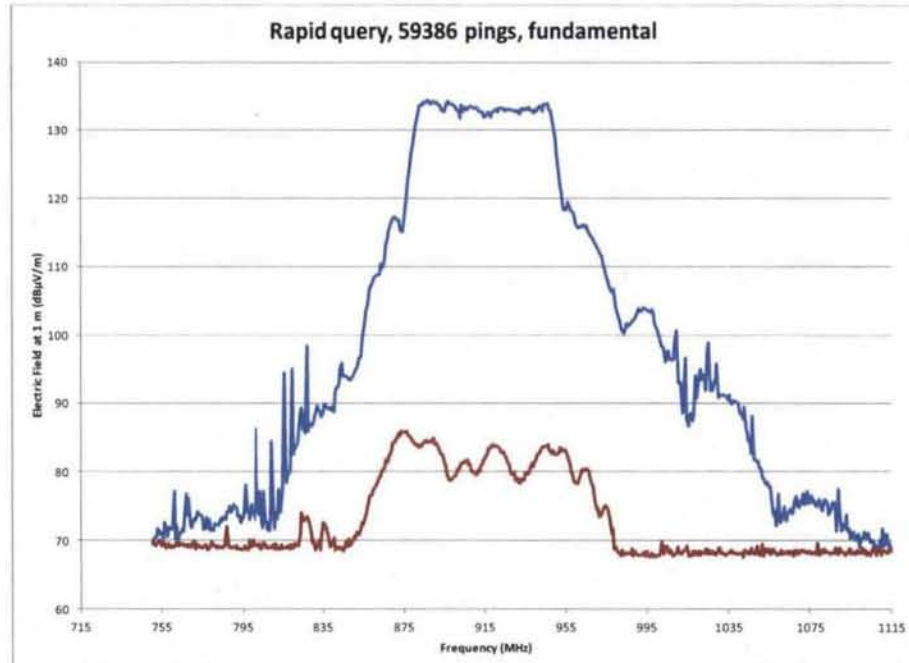


Figure 14. Rapid query spectrum, fundamental frequency; blue trace: transmitting, 2 hr 8 min; red trace: idle, 1 hr 10 min

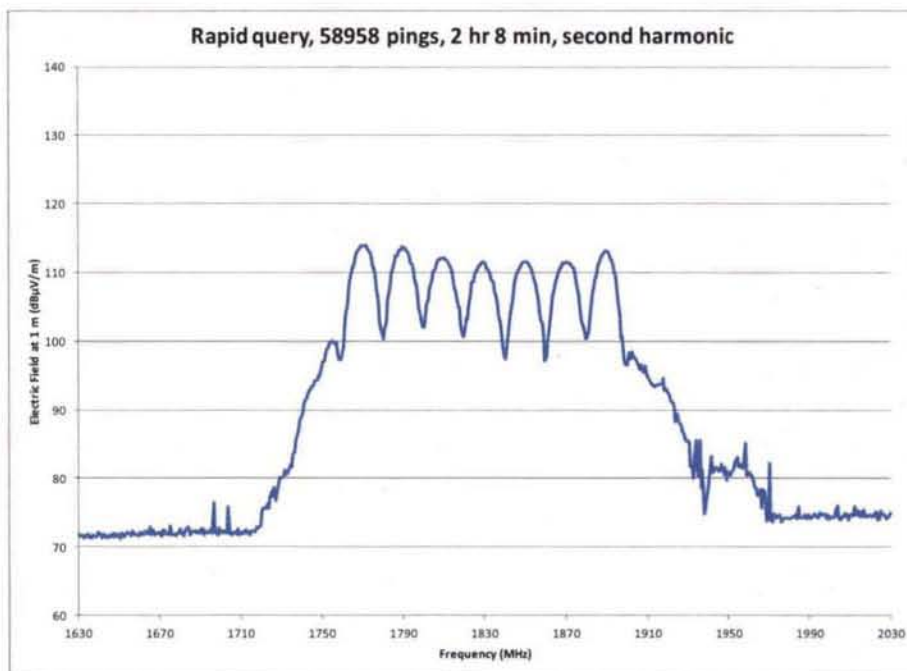


Figure 15. Rapid query spectrum, second harmonic frequency

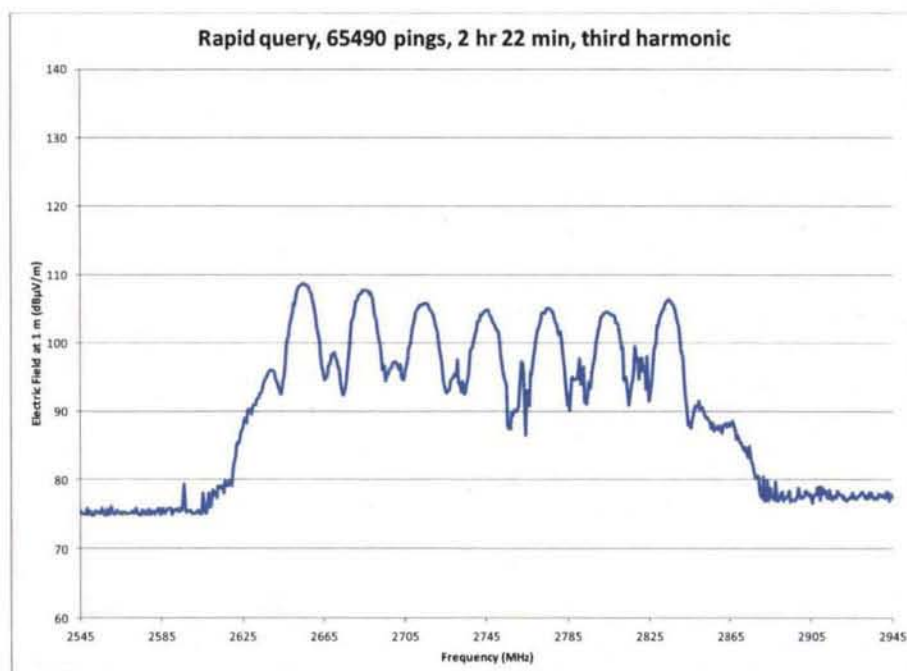


Figure 16. Rapid query spectrum, third harmonic frequency

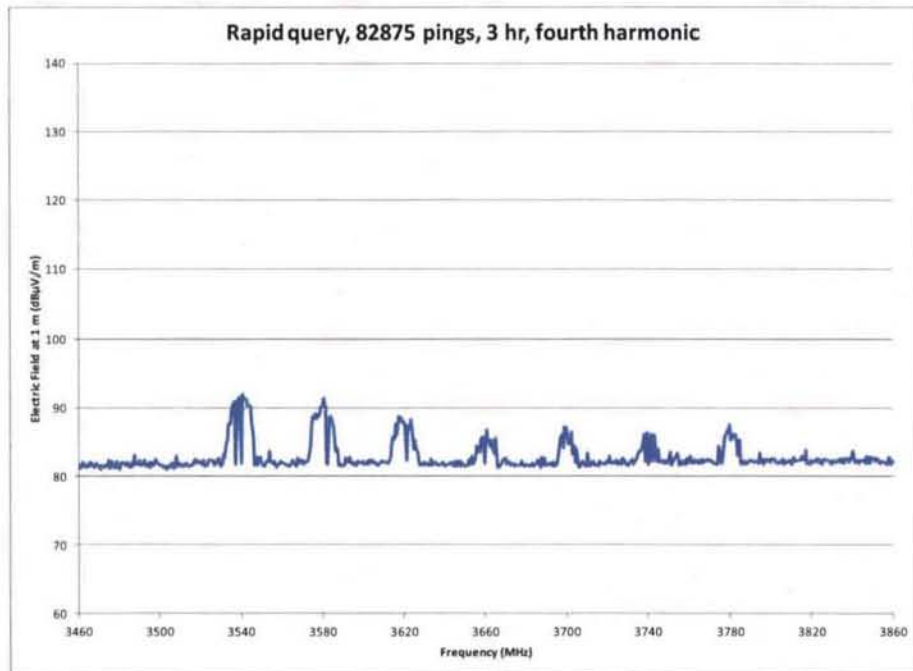


Figure 17. Rapid query spectrum, fourth harmonic frequency

2.3.3 Near-field Probe

Test Method

To determine the radiated emissions characteristics of the interrogator box, a series of near-field probe tests were conducted. The cover of the box was removed, and data was collected near the various circuit components and cables. Details of the test equipment are listed in Table 6 and Table 7.

Table 6. Near-field probe calibrated test equipment

Testing performed	10 Nov 2011
Agilent E7405A EMC Analyzer	
Metrology number	M84901
Calibrated	08 Apr 2011
Calibration due	08 Apr 2012
Span setting	30 MHz to 1 GHz
RBW setting	120 kHz
VBW setting	300 kHz
Coupling setting	AC
Capture time	Max hold for 2.5 min
Hewlett-Packard 8447F preamplifier	
Metrology number	M70131
Calibrated	14 Apr 2011
Calibration due	14 Jan 2012

Table 7. Near-field probe additional test equipment

Agilent 11940A Near-field Probe
09-09-407 60" cable
08-08-801 39.7" cable

Data, Observations, and Analysis

The collected data is an extensive series of spectrum traces, and is available in Appendix A.

2.4 Temperature Sensor Performance

Following RF characterization, a series of tests was conducted to evaluate the performance of the system when measuring the supplied wireless temperature sensors.

2.4.1 Stability, Range, and Orientation

Test Method

Determining the accuracy of the system requires an understanding of the expected noise level. To characterize the stability and noise of the temperature measurement, a single sensor was placed on the test table inside the chamber along with the interrogator's antenna (Figure 18). A paper template marked increments of 0.25 m away from the antenna, with outlines for the sensor's wooden base to indicate a series of test orientations (see Figure 19; Figure 18 shows the sensor in orientation 1). The first four orientations were used for the initial testing. Orientations 5 and 6 were added to account for the third axis of rotation. Orientation 7 was added to test for ground plane effects (see Section 2.4.2).

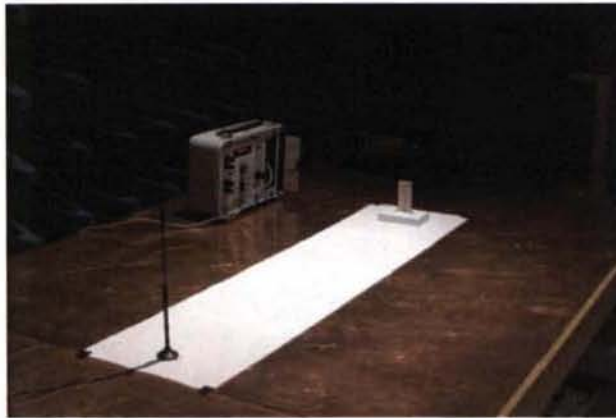


Figure 18. Stability, range, and orientation test setup

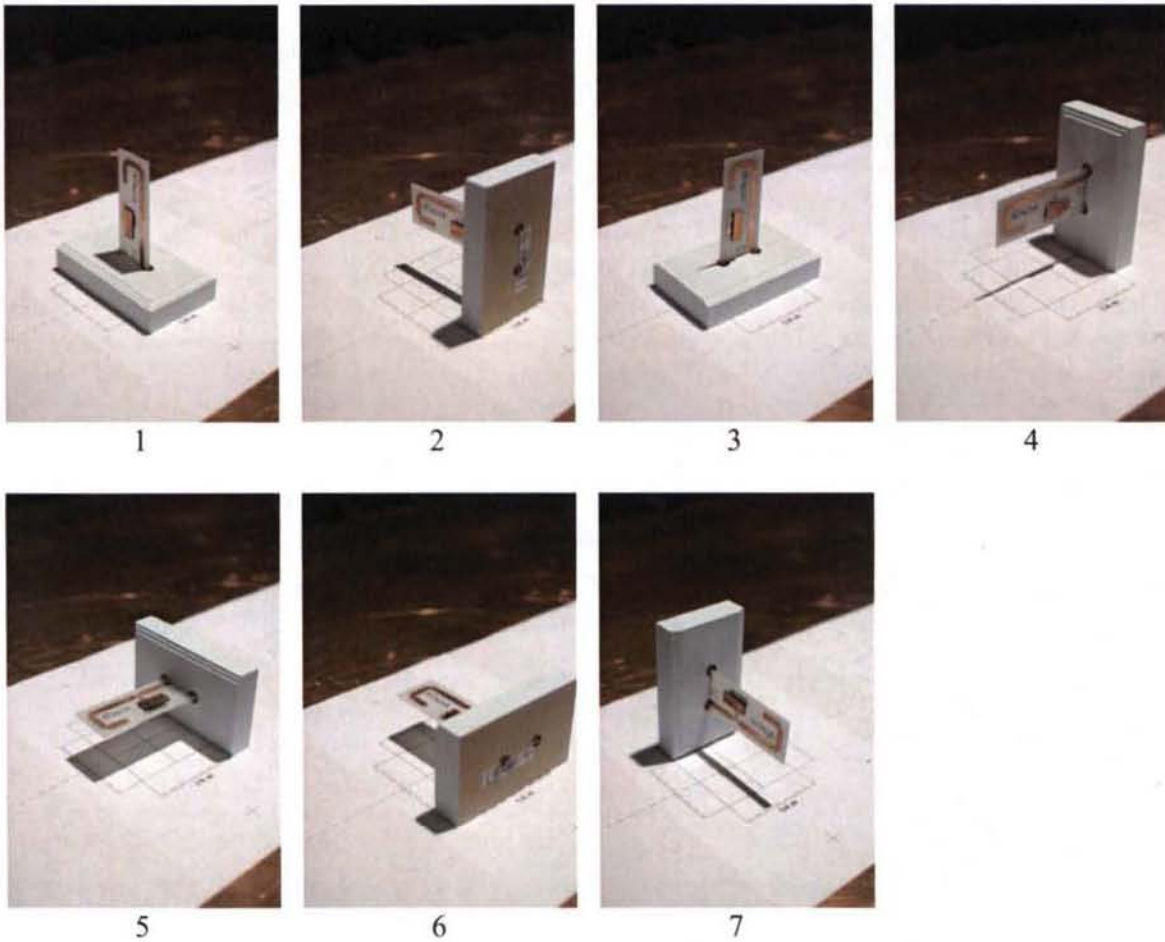


Figure 19. Sensor test orientations

As the distance and orientation were varied, different levels of noise were observed in the measured temperature data. The operating software was modified to record the temperature data, the correlation peak (the software's internal measure of the signal strength), and the corresponding date and time to a text file for subsequent analysis. The display portion of the software was also modified to allow other software to be operated on the same computer, which was required for temperature testing. These changes resulted in improved speed, with data for a single sensor processed typically within four seconds, as a significant portion of the data processing time in the supplied software is spent updating the display. A sample data capture is shown in Figure 20.

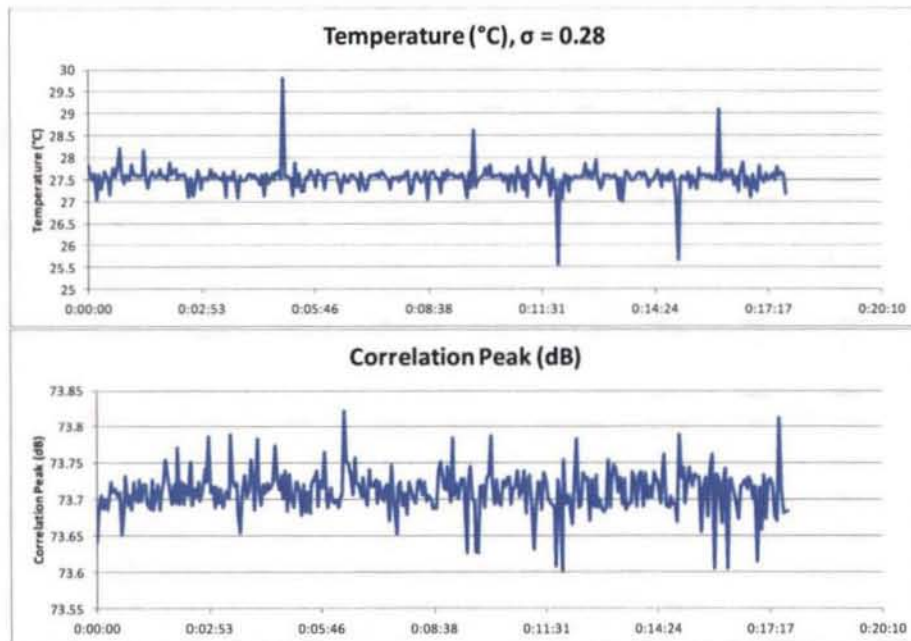


Figure 20. Sample data

The standard deviation of the data was taken to be a reasonable measure of the noise level, given that the chamber temperature is reasonably stable over the time periods tested here. To confirm the stability of the room temperature, a thin foil thermocouple (Table 8) was attached to the back of one of the sensors using vinyl tape (Figure 21), and the temperature stability was observed during the data capture. Typical variation of the room temperature was no more than 0.2 °C, and the measured temperature was observed to vary slowly⁵. Thus the large excursions ("spikes") shown in the captured temperature data were taken to be errors rather than actual variation of the room temperature.

⁵ These observations, for sensor NS402, were not recorded in the data sheets. Later, ambient temperature readings (with the thermocouple not attached to the sensor) were recorded at the beginning and end of the data captures.

Table 8. Temperature stability instrumentation

Omega Omni-Cal	
Metrology number	M08216
Calibrated	01 Sep 2011
Calibration due	01 Feb 2012
Testing performed	5-12 Oct 2011
Omega Cement-On Foil Thermocouple	
Model number	CO1-T
Wire size	30 gauge
Foil thickness	0.0005



Front view



Back view

Figure 21. Thermocouple attachment for stability test (sensor NS402)

Data, Observations, and Analysis

Noise performance was observed to vary significantly with sensor orientation (Figure 22). This was expected, since the interrogator antenna is a dipole and thus strongly polarization-dependent. The SAW sensor antenna is a folded dipole. Orientation 2, where the sensor was perpendicular to the antenna, was the worst overall. Orientations 5 and 6, where the sensor was parallel to the table, also performed poorly, but showed some improved performance at close range (Figure 23). Note that the testing matrix (see Appendix B) was not exhaustive in combinations of orientation and distance. It was also observed that the orientation dependence was different for the different sensors tested (Figure 24). For the four supplied sensors tested with one meter between the antenna and sensor, NS401R and NS404 showed the strongest orientation dependence, while NS402 was comparably insensitive to orientation. Orientation 7 was not tested in this dataset.

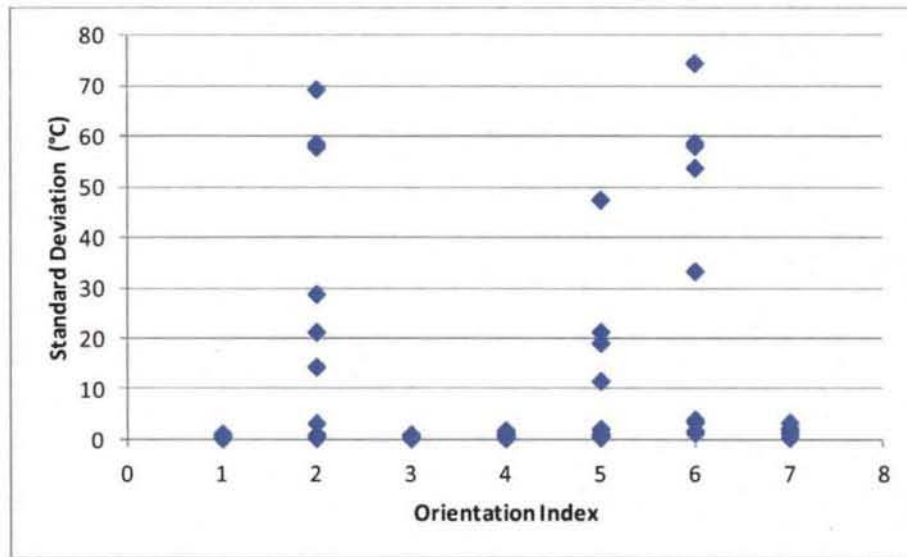


Figure 22. Sensor noise vs. orientation; includes range/stability tests on table (71 runs)

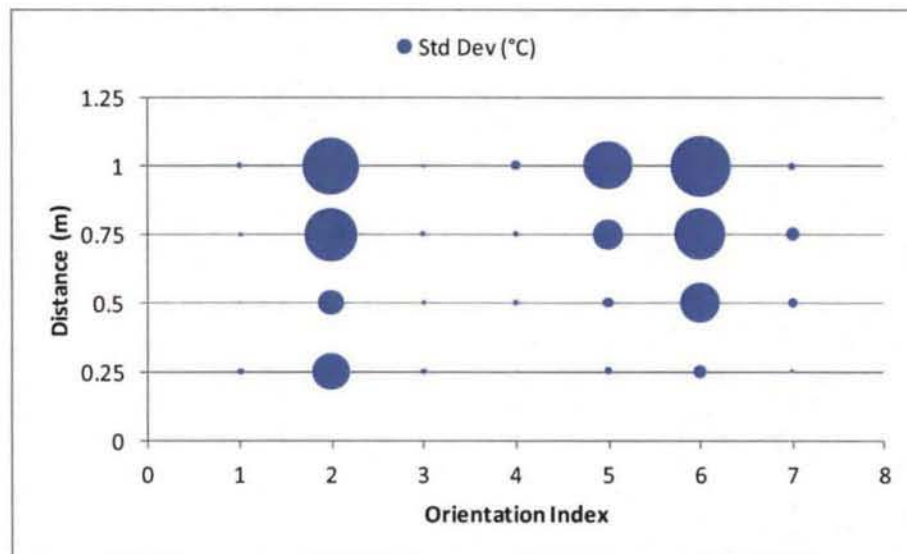


Figure 23. Sensor noise vs. distance vs. orientation; includes range/stability tests on table (71 runs)

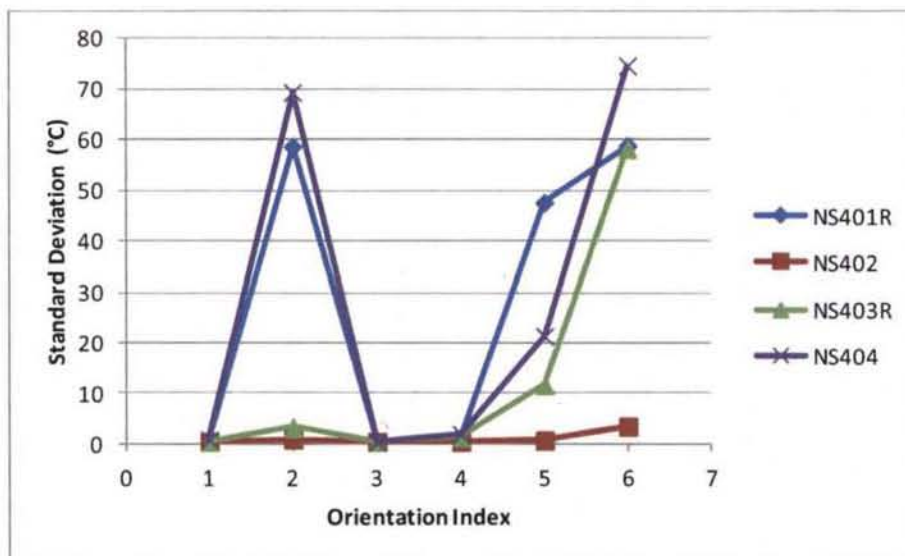


Figure 24. Sensor noise vs. orientation; includes range/stability tests at 1 m distance on table (24 runs)

2.4.2 Ground Plane Effects

Test Method

It was noted that the four supplied sensors were mounted in their wooden bases slightly differently: the vertical “arm” of the folded dipole structure was towards the left on the even-numbered sensors NS402 (see Figure 21) and NS404, but towards the right on the odd-numbered sensors NS401R (see Figure 19) and NS403R. This was not intentional, and not expected to significantly affect the performance for some orientations (1, 3, and 5), but could affect the performance of the orientations where this discrepancy changed the distance between the vertical arm of the dipole and the surface of the table, which is a large ground plane. To determine the significance of this effect, results from orientation 2 were compared to orientation 7, which simulates the difference between the left- and right-handed mounting.

Data, Observations, and Analysis

A sample data comparison is shown in Figure 25, showing a vast difference in performance between the two orientations. For sensor NS404 with one meter between the antenna and sensor, orientation 2 produced no useable data (standard deviation of 69.3 °C), but orientation 7 produced reasonably good data with a standard deviation of 1.2 °C. Thus ground plane effects must be considered with this system design, and future testing should ensure consistent mounting orientation of the sensors.

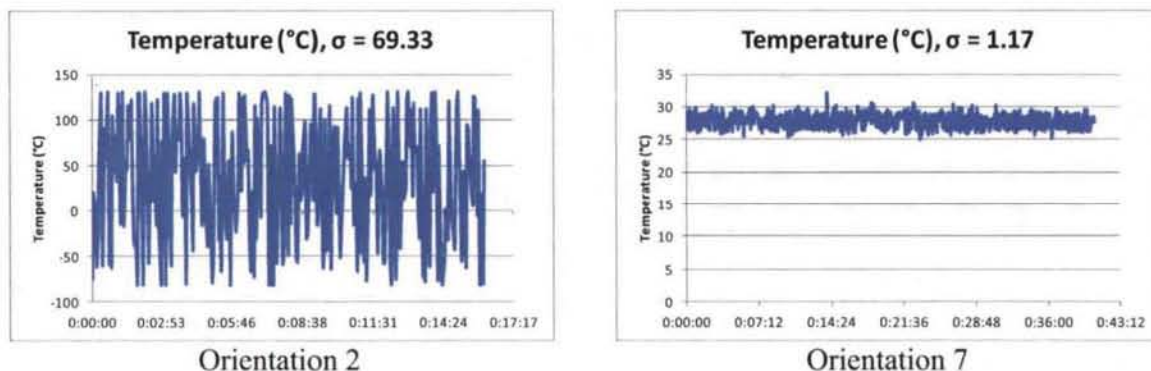


Figure 25. Ground plane sensitivity results (range/stability, table, NS404, 1 m)

2.4.3 Free-Space Range

Test Method

In addition to the testing on the copper-surfaced table in the EMI chamber, a series of free-space tests were conducted to characterize the maximum usable range of the sensors. To reduce ground plane effects, the interrogator antenna and sensor were mounted on separate plastic tripods (Figure 26), and moved the maximum available distance apart along the diagonal of the chamber. Temperature data was collected, and the sensor tripod was moved closer to the interrogator sensor; this was repeated several times. At each test distance, the sensor was visually aligned facing the interrogator antenna.



Interrogator antenna



Sensor

Figure 26. Free-space range setup

Data, Observations, and Analysis

A summary chart of the free-space testing is shown in Figure 27. Note the clear threshold between 4 m and 5 m, which may also be seen in the sample data charts in Figure 28. Beyond 4 m, it would be difficult to recover useable data; at 4 m and less separation, a clear trend is visible, with a decreasing noise band as the separation distance is decreased.

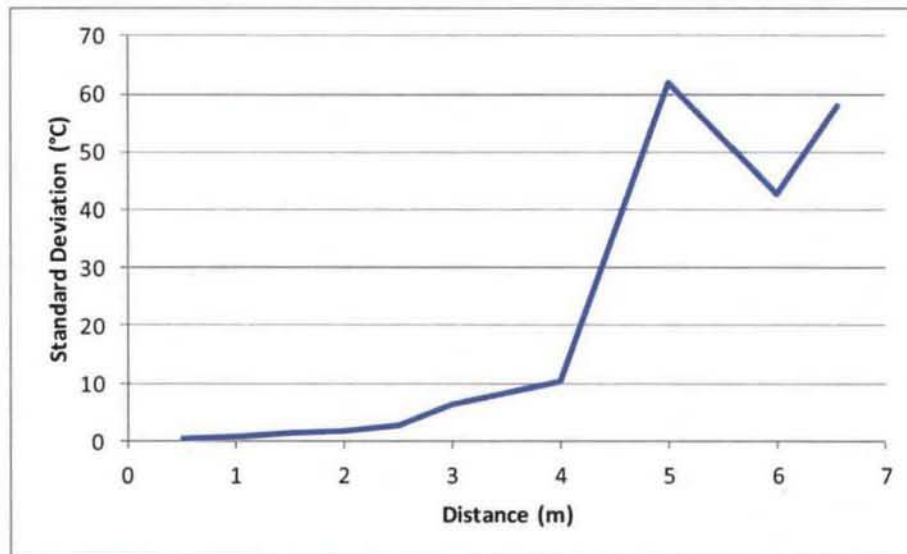


Figure 27. Free-space testing results summary; NS401R and provided antenna mounted on plastic tripods

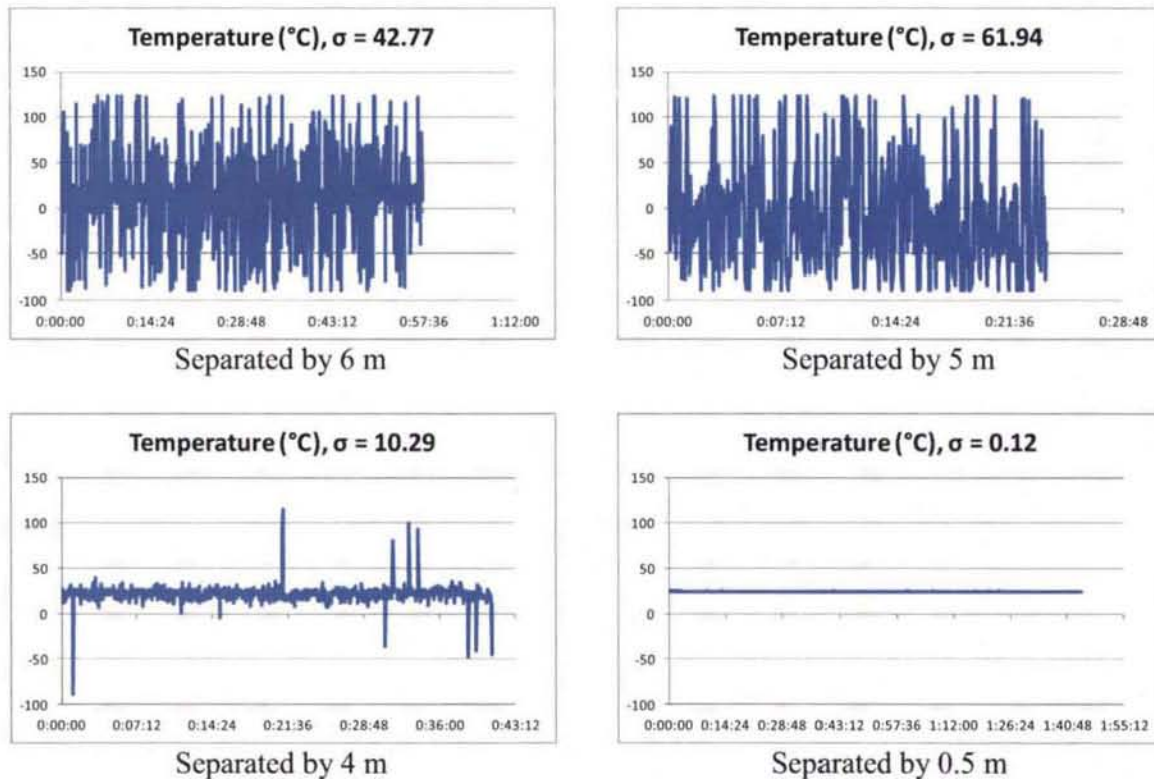


Figure 28. Free-space testing sample results; NS401R and provided antenna mounted on plastic tripods

2.4.4 Aggregate Results

Test Method

One challenge noted during testing is that the operating software may produce rapidly varying results if the signal level is low. This is because the software makes no attempt to determine whether a given sensor is present or producing useful data; rather, it determines the best correlation of the received signal with the expected sensor response, and reports this correlation as the result. The strength of the correlation is measured in the software as the “correlation peak” (in dB). To determine whether this would be a useful measure of data quality, the results of the testing in Sections 2.4.1 through 2.4.3 were plotted as the standard deviation of the temperature measurement versus the correlation peak.

Data, Observations, and Analysis

Results of this analysis are shown in Figure 29; a detailed view of the lower-right portion of the chart is shown in Figure 30. The standard deviation of the data increases smoothly below 55 dB correlation peak, then increases rapidly below 40 dB. This should make it possible to give a reasonable confidence interval on a given measurement based on the value of the correlation

peak. Because this measurement process is considered to be coherent, it may also be possible to dynamically adjust the integration time to improve results when the correlation peak is low.

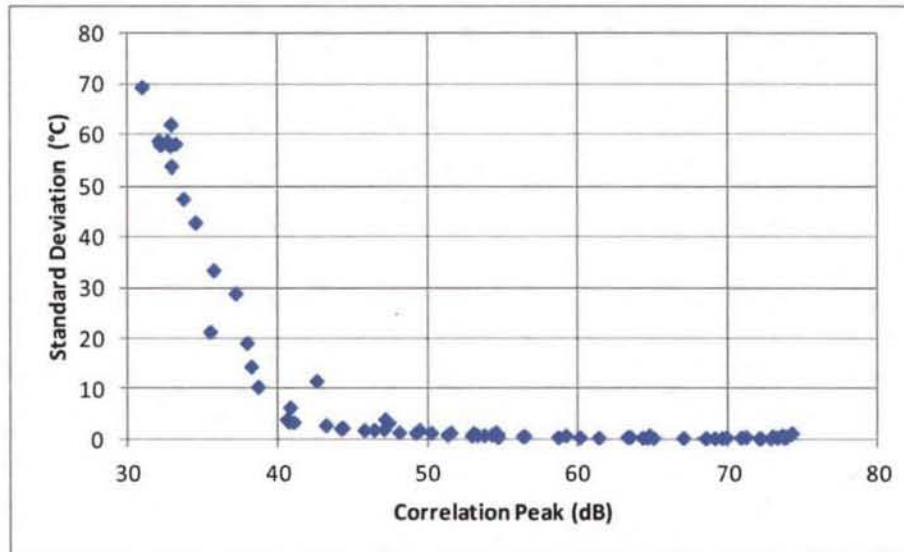


Figure 29. Sensor noise vs. signal; all range/stability data with correlation peak included (77 runs)

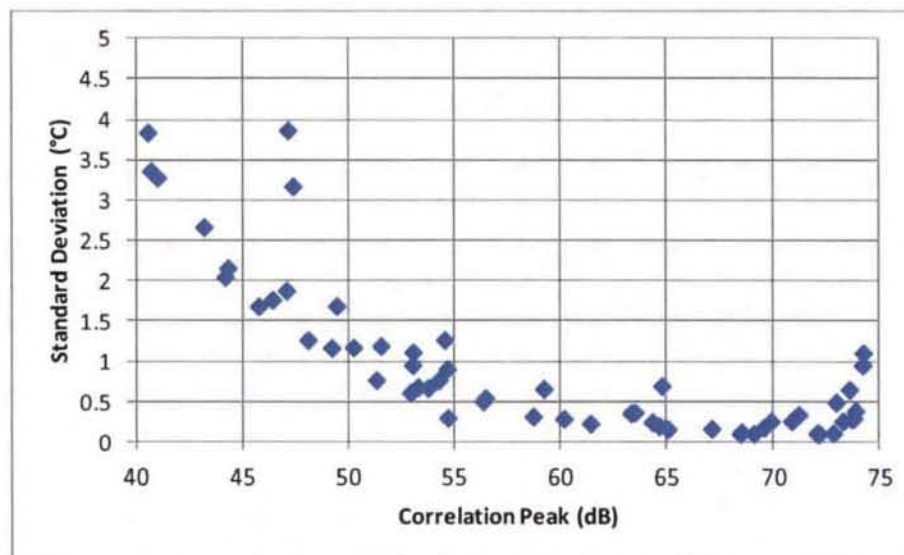


Figure 30. Sensor noise vs. signal (detailed view); all range/stability data with correlation peak included (77 runs, 60 shown here)

2.4.5 Temperature Performance

Test Method

To characterize the temperature performance of the SAW sensors, a test setup was developed to expose the sensors to a controlled temperature environment while maintaining an RF path to the interrogator antenna. Placing the antenna inside an existing temperature chamber proved to be impractical, since the antenna height was greater than the available inside height of the chamber, and since the achievable distance from the antenna to the sensor was very limited. Instead, the sensor was placed directly behind the chamber window, and the interrogator antenna was mounted on a plastic tripod one meter away (Figure 31). This proved to give good signal levels while allowing flexibility in the antenna placement. To measure the temperature of the sensor, a Type T thermocouple was clamped to the substrate of the sensor, and wired to a Keithley 2002 multimeter equipped with a thermocouple scan card (Table 9). The environmental chamber, a Sun Electronic Systems EC12 (Table 10), uses liquid nitrogen for cooling and a resistive element for electric heating. Steps were taken to maximize safe operations, including setting up the liquid nitrogen supply cylinder and nitrogen exhaust vent outside the EMI chamber. Because liquid nitrogen had not been previously used inside the EMI chamber, this configuration required additional Safety review. To demonstrate the feasibility of the general approach, the chamber was tested in heat-only mode, which does not require liquid nitrogen. To cool the chamber, an ebm-papst 8218J/2H4 fan was attached to the side of the chamber, facing into the side feedthrough port. This fan was powered by an Agilent E3645A DC power supply.



Overview



Sensor

Figure 31. Temperature test setup, initial version

The RF power levels broadcast by the interrogator are above that generally recognized as safe for personnel to be inside the EMI chamber, thus the whole test setup had to be remotely operated.

The Sun chamber, Agilent power supply, and Keithley multimeter all have GPIB interfaces, and this presented the best option for control and monitoring. A Hewlett-Packard 37203A HP-IB extender (HP-IB is compatible with GPIB) was placed in the chamber and cabled to the test equipment; the coaxial connection was connected to a bulkhead feedthrough on the chamber wall. This was then connected to a second extender outside the chamber. This allowed the laptop and its GPIB interface to interface with the test equipment. An existing LabVIEW virtual instrument was available to monitor the Keithley multimeter, but new virtual instruments had to be developed to control the Sun chamber and Agilent power supply. All three were capable of running simultaneously with the MATLAB-based SAW sensor operating software.

Table 9. Calibrated instrumentation for temperature test

Testing performed	19 Oct 2011
Keithley 2002	
Metrology number	M66382
Calibrated	10 Jun 2011
Calibration due	10 Nov 2011
Keithley 2001-TCSCAN	
Metrology number	M71628
Calibrated	10 Jun 2011
Calibration due	10 Feb 2012

Table 10. Additional equipment for temperature test

Sun Electronic Systems EC12 test chamber
Two, Hewlett-Packard 37203A HP-IB extenders
National Instruments PCMCIA-GPIB interface card
Type T thermocouple (soldered from wire)
ebm-papst 8218J/2H4 fan
Agilent E3645A DC power supply
Irwin Quick-Grip 1½" – 38 mm clamp

Data, Observations, and Analysis

Initial temperature test results are shown in Figure 32. Note that the SAW sensor measurement tracks well with the thermocouple measurement, but with an error which appears to increase as temperature increases. This may reflect an error in the assumed temperature coefficient of the SAW sensor, -94 ppm/°C. Further testing, with extended temperature ranges, may be conducted with future task order funding, pending Safety approval, and once an improved sensor mount is constructed.

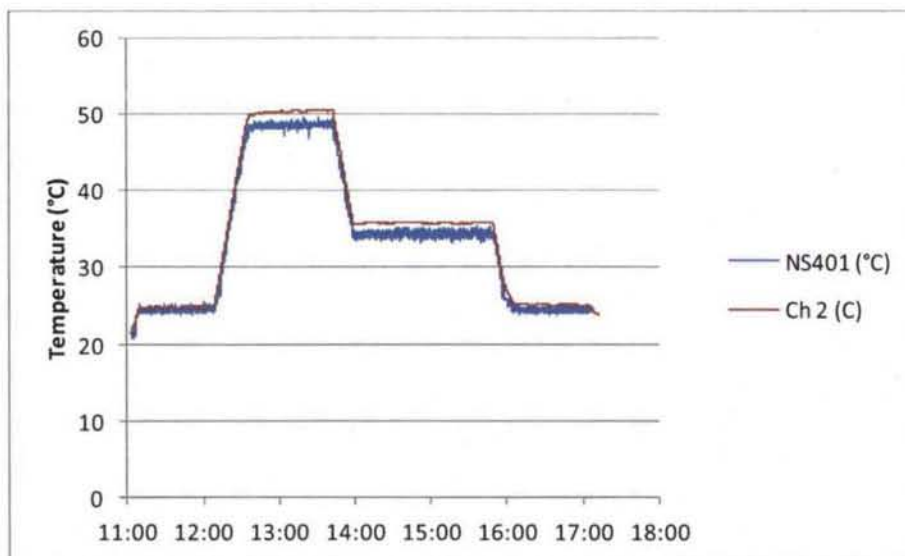


Figure 32. Temperature test results; blue trace: SAW sensor; red trace: thermocouple

2.4.6 Additional Sensors

A set of eight additional temperature sensors (two each of four codes) were ordered as part of this testing; these sensors were received from UCF on 16 November 2011, and will be tested if future task order funding permits.

2.5 Hydrogen Sensor Performance

A set of four hydrogen sensors was ordered from UCF; these sensors were received on 23 November 2012. Sensor serial numbers are listed in Table 11. Sensor BHF401-062712 was damaged in handling in the lab before testing could be conducted; it has since been returned to UCF for possible repair. Sensors are referred to in the testing herein by their code number (e.g., BHF401) without the date of manufacture.

Table 11. Hydrogen sensor serial numbers

BHF401-062712
BHF402-052312
BHF403-052312
BHF404-052312

2.5.1 Hydrogen Test Setup

Testing of hydrogen sensors, as well as testing for effects of local ambient pressure, requires a pressure enclosure for the sensors. This enclosure must be capable of safely withstanding test pressures, yet must pass the RF signals of the interrogator and sensor. Various materials were

researched for this purpose; options included a sight glass or chemical reaction vessel, but these proved to be too expensive for the available funding. An enclosure primarily constructed of plastic pipe was considered a good, less expensive option. Though it is reasonably available and inexpensive, clear PVC tubing was rejected because PVC is not considered safe for compressed gas service. This is due to the failure mode of PVC, brittle fracture, which may produce shrapnel. Market research found two plastic piping systems which are specifically designed for compressed gas service: Asahi America Air-Pro (HDPE) and IPEX Duraplus Air-Line (ABS). Duraplus Air-Line was preferable for this testing since it may be assembled via solvent welding, without the purchase or rental of additional equipment. The solvent and cleaner both use methyl ethyl ketone (MEK), which required Safety approval; its use was approved outdoors, away from facility entrances, with nitrile gloves preferable for handling. The upper part of the pressure enclosure consists of a cap, a section of tubing, and a stub socket flange. This section is secured using a steel backing plate around the stub flange, bolted through to an aluminum base, trapping a gasket for sealing the enclosure. This assembly allows the RF signals to pass through while allowing service up to 150 psi with good safety margin; the piping system is rated up to 185 psi continuous service at room temperature. All testing performed thus far has been with the downstream port of the last test fixture open to the room, thus the actual internal pressure is quite low. One of the completed fixtures is shown in Figure 33.



Overview



Sensor mounted in fixture

Figure 33. Hydrogen test fixture

Five compressed gas cylinders from local stock were used for the testing herein; the commodities are listed in Table 12. Details of the calibrated and uncalibrated test equipment are shown in Table 13 and Table 14, respectively.

Table 12. Commodities used for hydrogen testing

Commodity	Actual Contents
Breathing air	Breathing air
2% hydrogen in air	2.01% hydrogen, balance air
3% hydrogen in air	3.02% hydrogen, balance air
50% helium, 50% air	62.6% helium, 37.4% air
2% hydrogen in nitrogen	2.00% hydrogen, balance nitrogen

Table 13. Calibrated test equipment for hydrogen testing

Testing performed 24 Jan-20 Feb 2013
CalTechnix⁶ molbox1
Metrology number M70271
Calibrated 11 Oct 2012
Calibration due 11 Oct 2013
DH Instruments⁷ molbloc 30 slm-SWG-V-Q
Metrology number M70269
Calibrated 11 Oct 2012
Calibration due 11 Oct 2013
DH Instruments molbloc 1 slm-SWG-V-Q
Metrology number M70268
Calibrated 11 Oct 2012
Calibration due 11 Oct 2013
Fluke 8840A Multimeter
Metrology number M07563
Calibrated 17 Jul 2012
Calibration due 17 Mar 2013
Yokogawa 7651 Programmable DC Source
Metrology number M89084
Calibrated 31 Oct 2012
Calibration due 30 Sep 2013

⁶ The molbox series is now produced and supported by Fluke Calibration.

⁷ DH Instruments is now part of Fluke Calibration.

Table 14. Additional test equipment for hydrogen testing

Mnemonics, Inc. model 990-1139-001 SAW Transceiver System	
Serial number	001
Sierra Instruments C100L-DD-4-OV1-SV1-PV2-V1-S0-C0-GS-CC	
Serial number	106456
Range	10 SLPM
Sierra Instruments C100L-DD-4-OV1-SV1-PV2-V1-S0-C0-GS-CC	
Serial number	106457
Range	10 SLPM
MKS Instruments M100B01313CR1BV	
Serial number	021578273
Range	1000 SCCM N2
Agilent E3631A DC Power Supply	
Serial number	MY40040115
Whitey (now Swagelok) SS-44XF4 3-Way Valve	

2.5.2 Baseline and Range

Initial testing was performed to determine the noise level of the sensors when exposed to ambient air, both with the sensors spaced 90° apart and with them close together. The test enclosures were installed on the test fixtures, but no compressed gas supply was used. For each test, the test fixture was oriented with the sensor element above the inlet port, facing the Interrogator antenna (see Figure 34). The test table in the large EMI chamber is approximately 1.2 m by 4 m, which supports tests with the sensors spaced 90 degrees apart at a distance of 0.5 m, as well as tests with the sensors close together at distances up to approximately 3.5 m, as shown in Figure 35; tests were conducted up to 3 m, as shown in Figure 36.

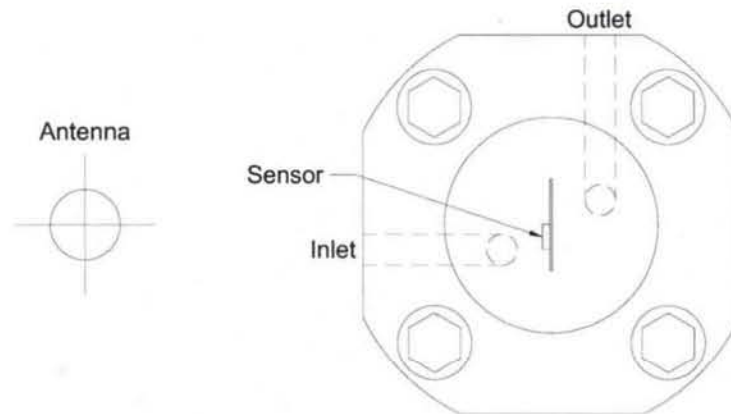


Figure 34. Test fixture orientation (details omitted for clarity)

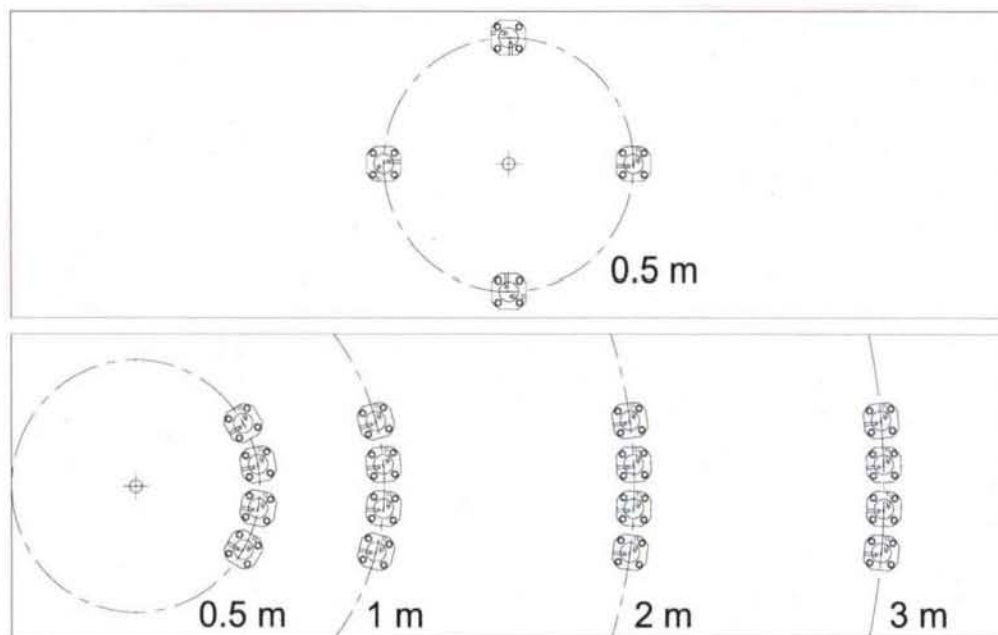


Figure 35. Baseline and range test arrangements, large chamber



Figure 36. Range test overview; 3 m test shown

Initial baseline testing showed that, at a distance of 0.5 m, both the 90° arrangement and the closely spaced arrangement had low levels of noise; see Figure 37 and Table 15. Sensors BHF402 and BHF404 had higher levels of noise in the close arrangement, while BHF403 had a higher level of noise in the 90° arrangement.

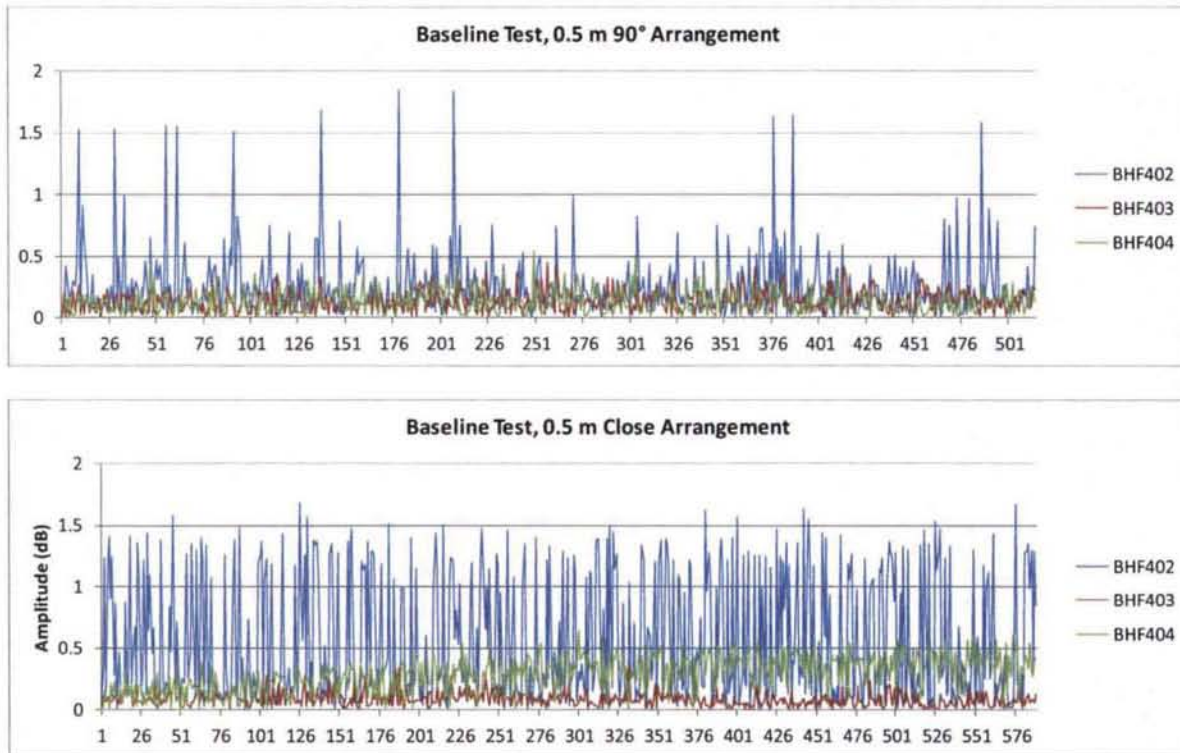


Figure 37. Baseline test results

Range testing was conducted with the sensors in the closely spaced arrangement, given the available space on the test table. Sensor noise increased with increasing distance, with one exception: sensor BHF402 had lower noise at 2 m than at 1 m; see Figure 38 and Table 15.

Table 15. Baseline and range test summary

Distance (m)	Arrangement	Average (dB)			Standard Deviation (dB)		
		BHF402	BHF403	BHF404	BHF402	BHF403	BHF404
0.5	90°	0.254	0.132	0.125	0.282	0.086	0.095
0.5	Close	0.550	0.082	0.287	0.515	0.059	0.144
1	Close	1.129	0.156	0.316	0.794	0.112	0.191
2	Close	1.047	0.618	0.368	0.541	0.435	0.276
3	Close	1.408	2.573	2.428	0.943	1.561	0.957

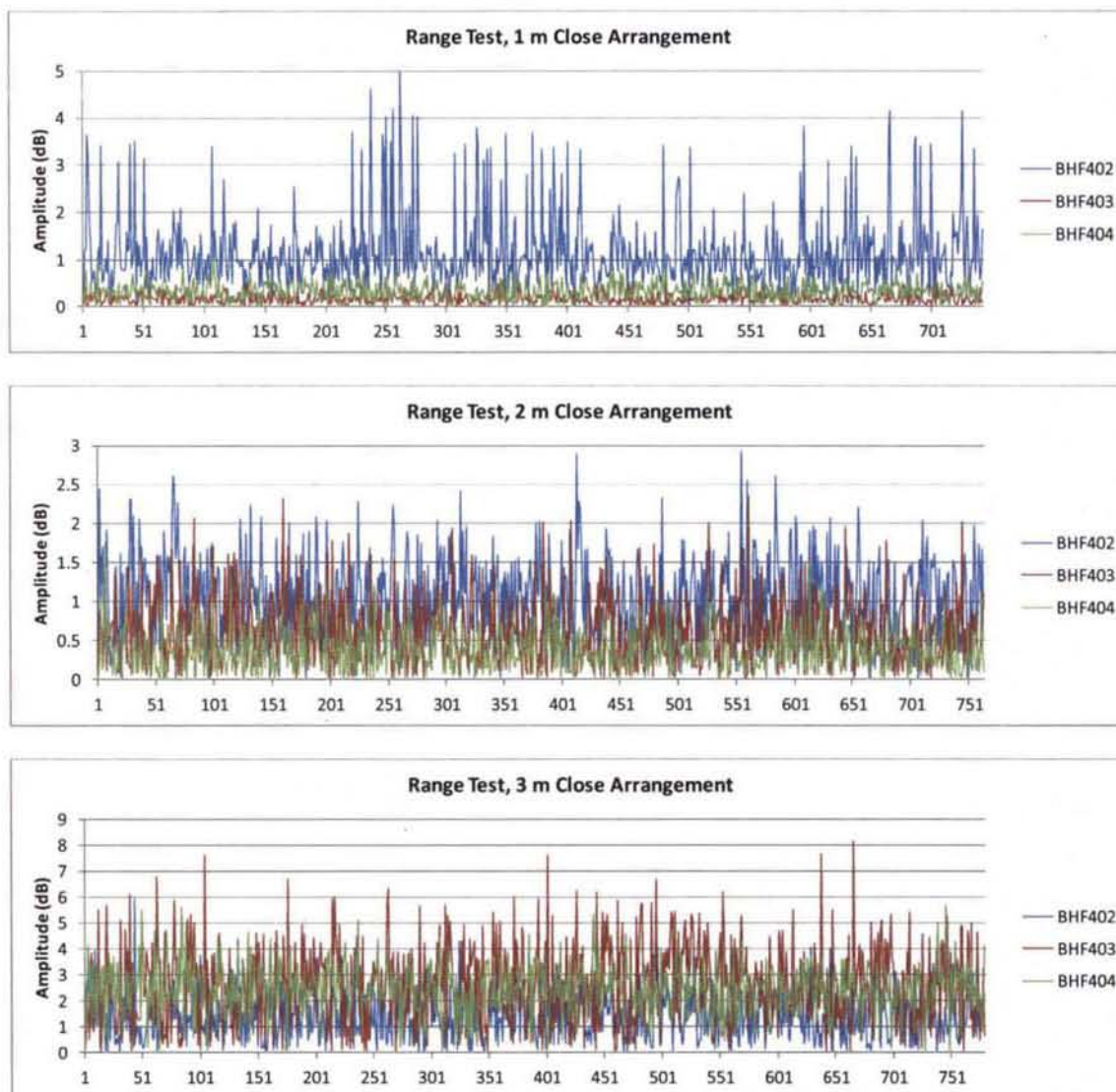


Figure 38. Range test results, amplitude

2.5.3 Hydrogen Exposure Test

The hydrogen exposure test exposes the sensor alternately to breathing air and a low concentration of hydrogen in air. Concentrations of 2% and 3% hydrogen in air were tested; premixed 1% hydrogen was not available at the time of testing. The actual commodities used are listed in Table 12 above. The test chamber is constructed from a piece of tubing approximately 6 inches (152.4 mm) long, with a nominal internal diameter of 51.6 mm. Thus the internal volume of the test chamber is approximately

$$\pi \times \left(\frac{51.6 \text{ mm}}{2} \right)^2 \times 152.4 \text{ mm} \times \left(\frac{1 \text{ L}}{10^6 \text{ mm}^3} \right) = 0.32 \text{ L},$$

plus the volume of associated tubing and fittings, and the flow path in the base of the test fixture. With a volume flow rate of 5 L/min, the test chamber volume will be changed out approximately 15 times per minute, or about once every 4 seconds, assuming uniform mixing. When testing multiple sensors simultaneously, to ensure each test fixture received the same flow rate, the fixtures were connected in a “daisy chain” configuration (see Figure 39), with the outlet of the first fixture connected to the inlet of the second fixture, and so forth. This was expected to introduce a small incremental delay in the sensors’ response due to the additional volume which must be exchanged with each subsequent fixture, and this effect was observed in the results.

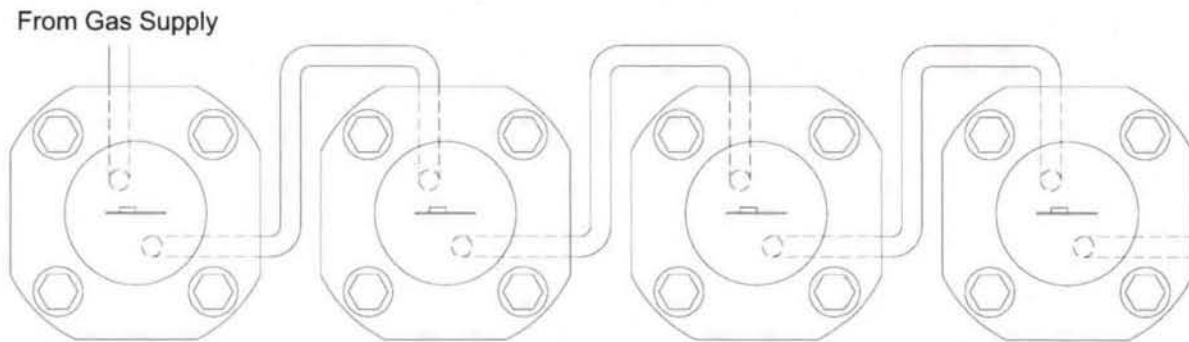


Figure 39. “Daisy chain” configuration

Calibrated mass flow controllers were not available at the time the testing was conducted, thus uncalibrated mass flow controllers were compared on the bench to a laboratory standard flow measurement device, the CalTechnix molbox, with DH Instruments molbloc elements. This system uses a laminar flow element to generate a flow-dependent differential pressure; the pressure at the inlet and outlet of the element is measured by precision pressure transducers, and the temperature is also measured to compensate for temperature effects. The bench comparison was performed with compressed nitrogen gas, and the set points corresponding to the desired mass flow were recorded. The difference in flow controller performance (known as the gas correction factor or GCF) between nitrogen and air or hydrogen was not considered significant for the testing herein; however, the digital Sierra mass flow controllers were reconfigured for air after the bench comparison, since this feature is integral to the controller.

The test schematic is shown in Figure 40, and images of the actual setup are shown in Figure 41. Cylinders of breathing air and mixed hydrogen gas are fed to a three-way valve using standard cylinder regulators. The output of the three-way valve supplies a mass flow controller set for a target flow rate of 5 SLPM. By switching the three-way valve, the gas flow can be alternated between breathing air and mixed hydrogen gas fairly quickly. The test profile (for 2% gas) and results are shown in Figure 42. The time scales are shown approximately aligned; the hydrogen sensor software does not record a timestamp.

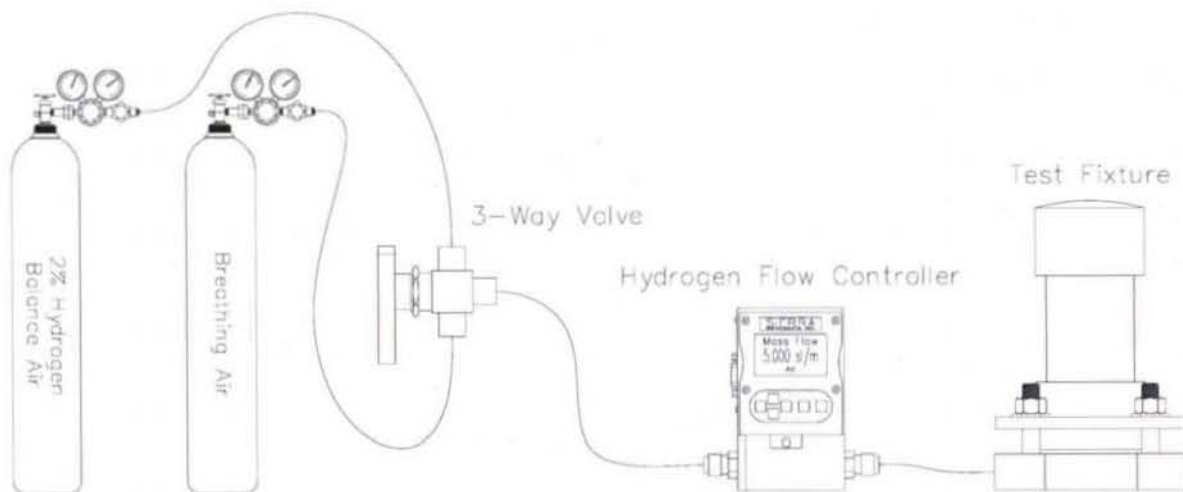


Figure 40. Hydrogen exposure test setup schematic

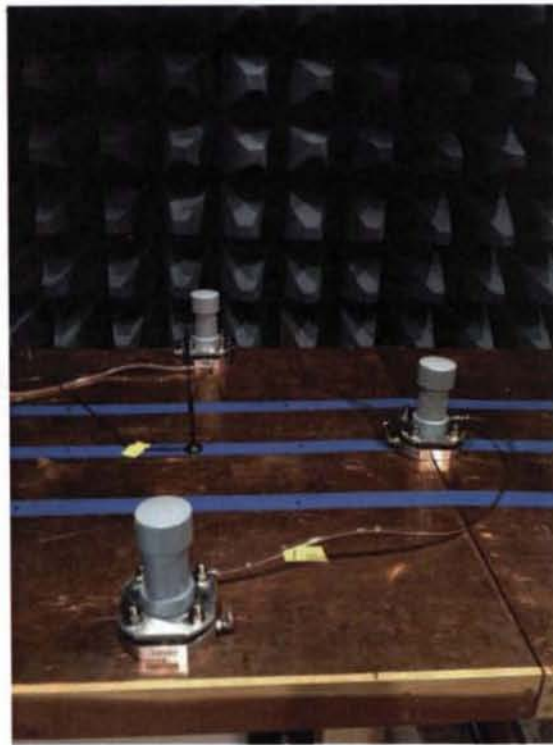


Figure 41. Hydrogen exposure test setup overview; 90° arrangement shown

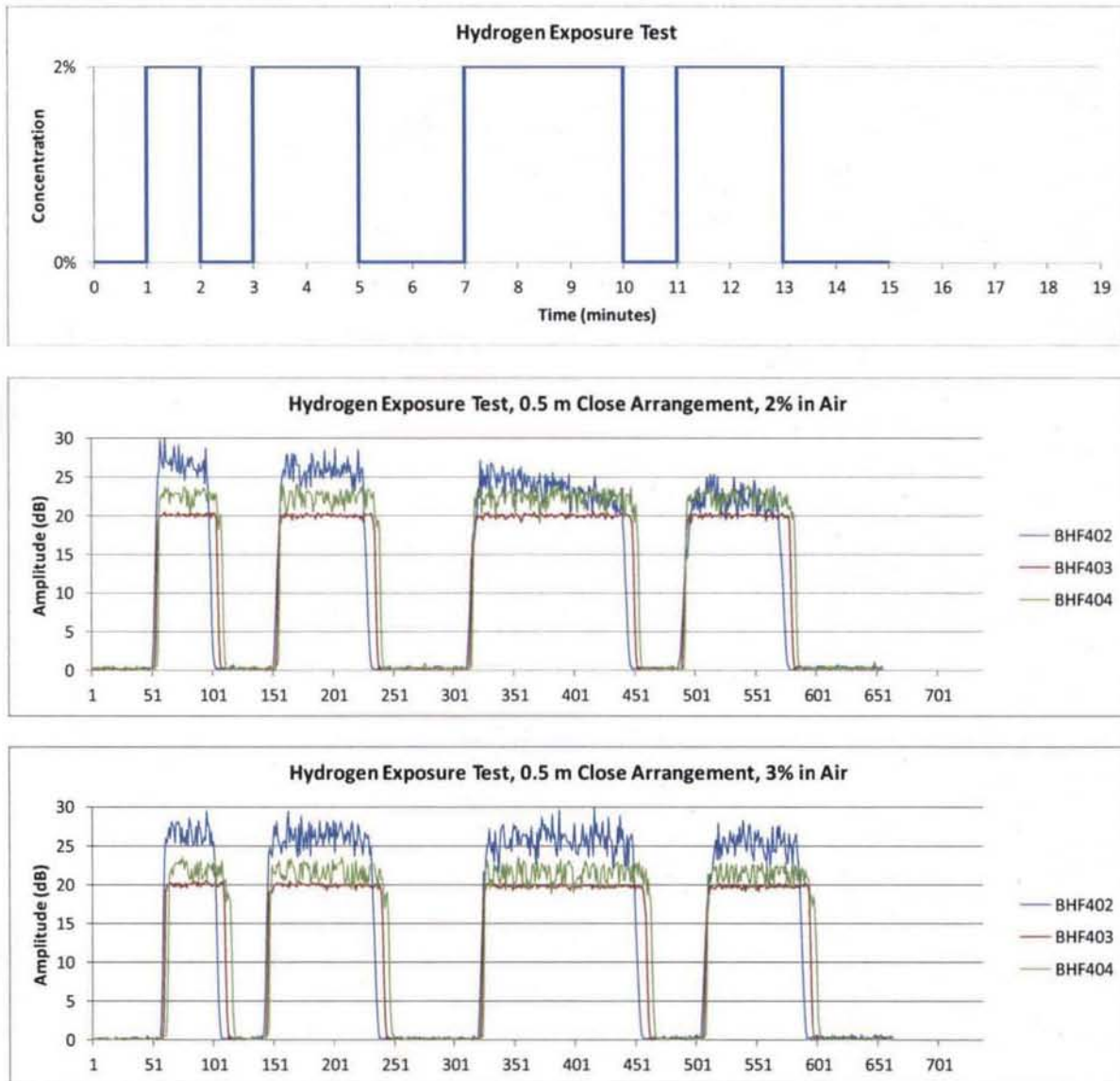


Figure 42. Hydrogen exposure test, input profile and results

The hydrogen sensors track the input profile well. The expected lag due to the daisy-chain configuration is most visible when the gas is switched off; sensor BHF402 was first in the flow path, and sensor BHF404 was last. Also visible in the 2% hydrogen results is some slope in sensor BHF402; the reason for this is not known, and it was observed in some of the other test results. The similar amplitude between exposure to 2% and 3% hydrogen indicates that sensors BHF403 and BHF404 were saturated with exposure to 2%; sensor BHF402 may have been saturated or nearly so.

2.5.4 Hydrogen Concentration Test

The hydrogen concentration test exposes the sensor to varying concentrations of hydrogen by mixing breathing air with pre-mixed 2% hydrogen in air. The mix ratio is adjusted by using two mass flow controllers with their outputs connected in a tee fitting, as shown in Figure 43. The total flow rate is maintained approximately constant, and the flow controller set points are adjusted at the same time.

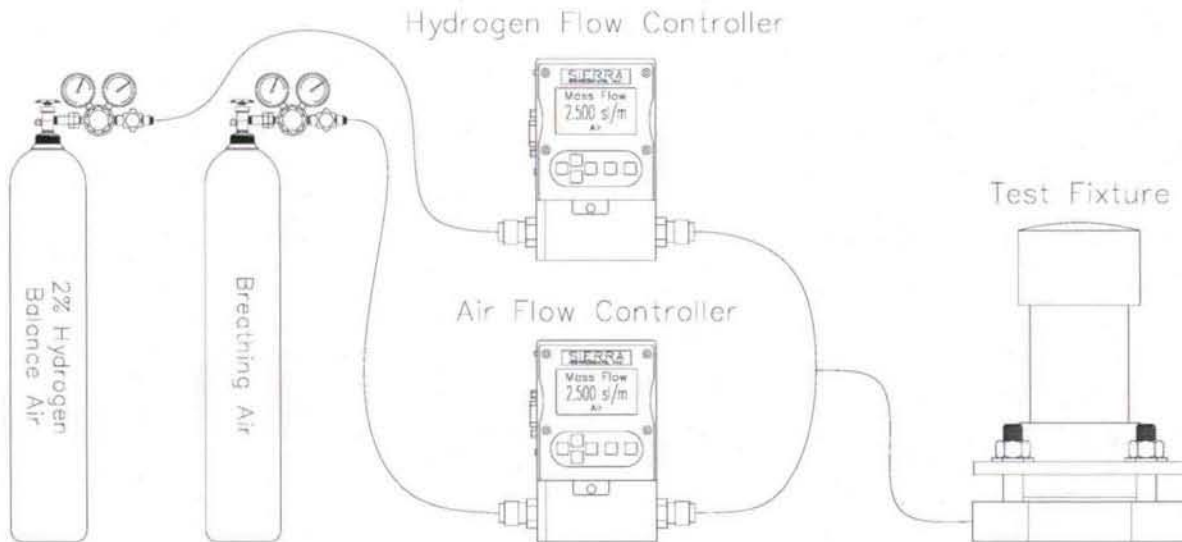


Figure 43. Hydrogen concentration test setup

The initial test was performed using a total mass flow rate of 8 SLPM, with the individual flow rates adjusted in steps of 0.8 SLPM to produce concentrations from 0.0% to 2.0% hydrogen in 0.2% steps. The higher flow rate (versus the exposure test) was due to the lower flow limit of the uncalibrated flow controllers. Sierra S/N 106457 was used for the 2% hydrogen, and Sierra S/N 106456 was used for the breathing air. The input concentration profile and the results of this initial test are shown in Figure 44; the time scales are approximately aligned. Saturation is observed for sensor BHF404 at 0.4% hydrogen and BHF403 at 0.6%; it is not clear whether sensor BHF402 saturates. Note also that hysteresis is observed in the data; the sensor performance with decreasing hydrogen concentration is different than the performance with increasing concentration.

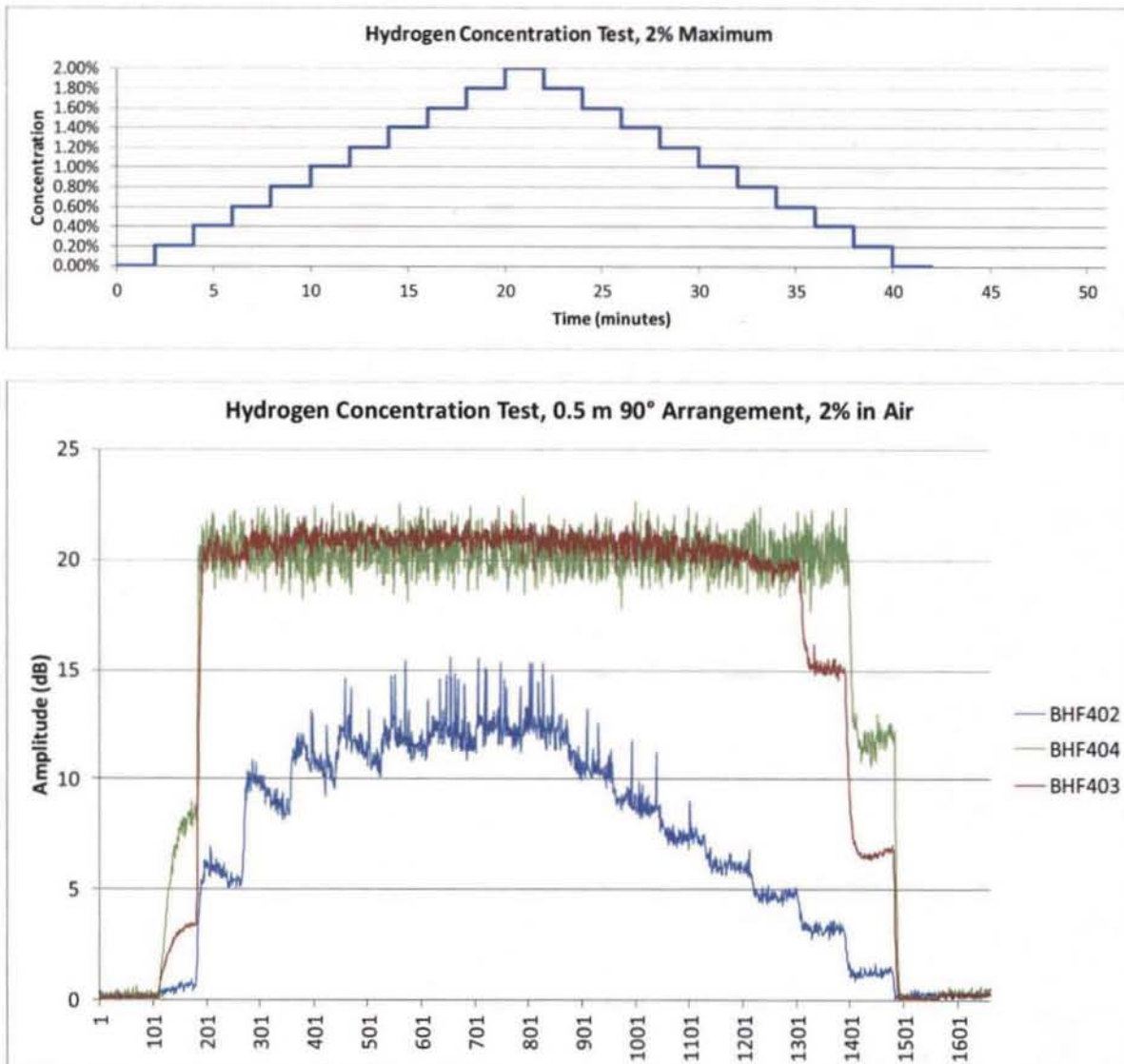


Figure 44. Hydrogen concentration test, input profile and results

Because sensors BHF403 and BHF404 saturated so quickly, a second test was performed to assess the performance of the sensors at much lower hydrogen concentrations. Because of the limitations of using the 10 SLPM mass flow controllers at very low flow rates, an MKS M100B mass flow controller with a full scale of 1 SLPM was used to supply the 2% hydrogen and the total mass flow rate was increased to 9 SLPM to optimize the use of the MKS flow controller's range. Sierra S/N 106456 was again used for the breathing air supply. Since the M100B is an analog controller, a Yokogawa 7651 was used to supply the set point input, and a Fluke 8840A displayed the flow controller's measured output. The flow rate for each controller was adjusted in 0.09 SLPM increments to produce concentrations from 0.10% to 0.20% hydrogen in 0.02%

steps. The choice of 0.10% minimum was based on a previous test run, not shown here. The final step of the input profile was 0.12% rather than 0.10% due to a crash of the Sierra flow controller's display module. The input concentration profile and the results of this second test are shown in Figure 45; the time scales are approximately aligned.

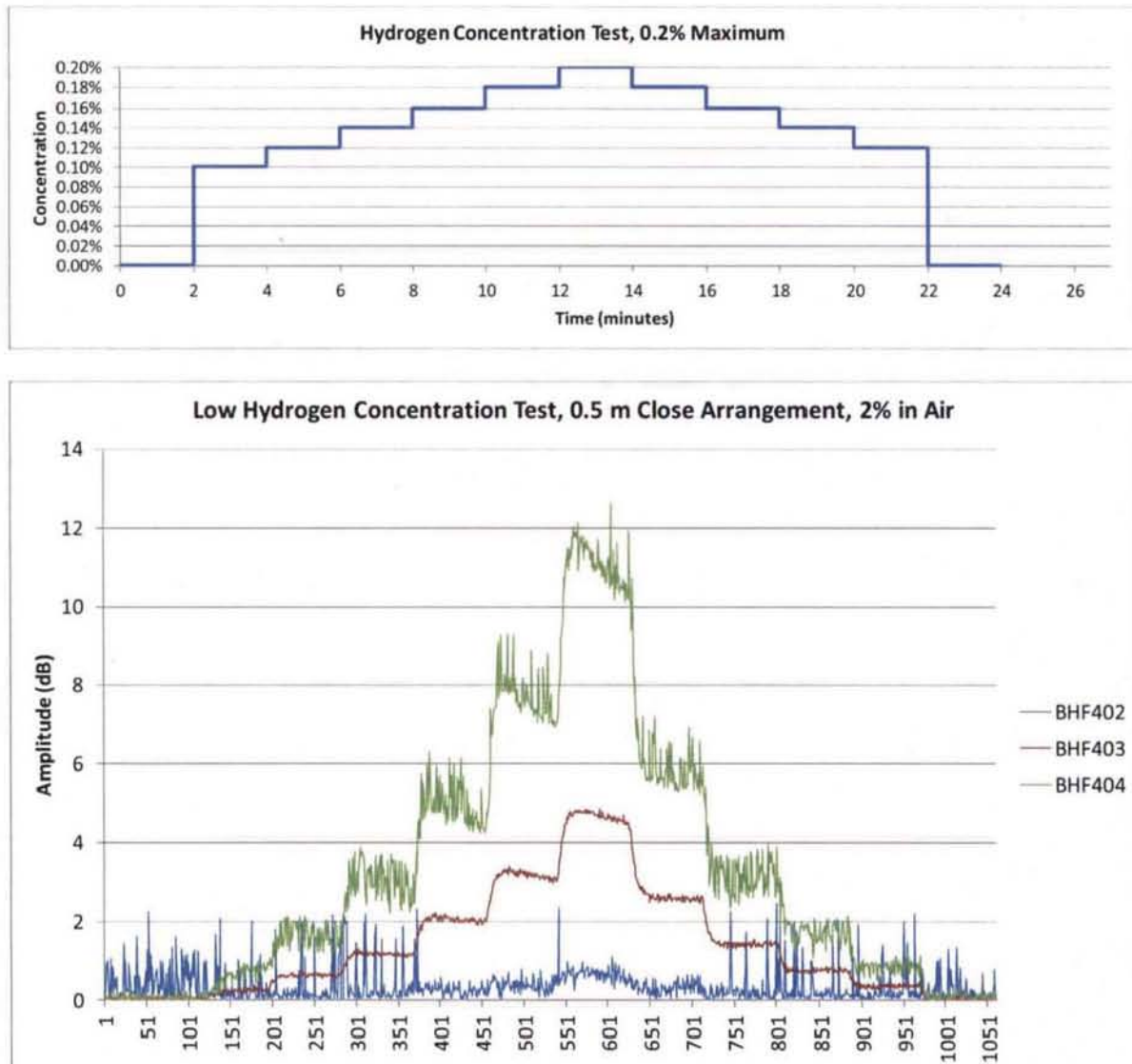


Figure 45. Low hydrogen concentration test, input profile and results

2.5.5 Additional Testing

The testing in this section was not documented with the same level of detail as the testing above, as it was intended as an initial evaluation of some of the other factors which may influence sensor performance. The first factor considered was helium. Existing hydrogen sensor

technologies used at KSC have, at times, exhibited poor performance when exposed to helium. Two tests were performed using a mixture of nominally 50% helium and 50% breathing air; the actual concentration (see Table 12) was 62.6% helium and 37.4% breathing air. A gas correction factor of 1.191 for 50% helium and 50% breathing air was calculated from Sierra's user manual and published data for breathing air composition. The first test used the MKS flow controller to supply the helium mixture, and Sierra S/N 106456 to supply breathing air, with a total flow rate of 9 SLPM. With a concentration mixed to 6.26% helium (based on the actual concentration), no response from the sensor was observed, as shown in Figure 46; the input concentration profile was not recorded. The slope observed in the data is similar to that observed in the baseline test.

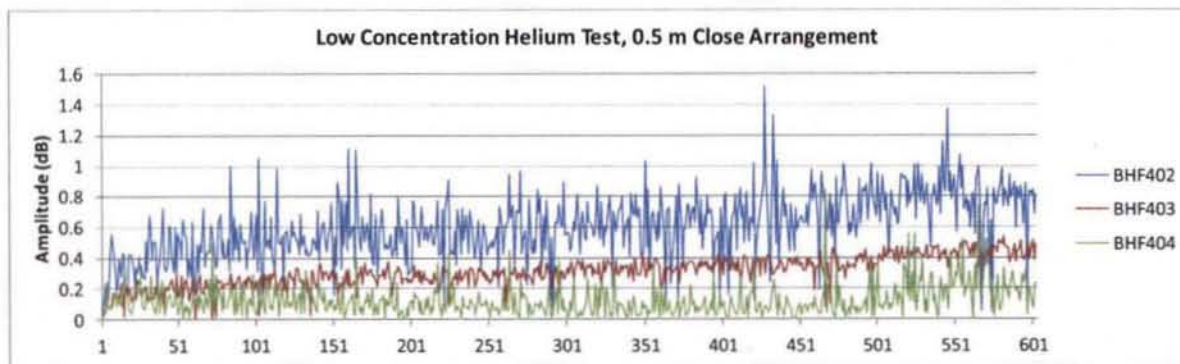


Figure 46. Low helium concentration test results

In the second test, the helium mixture was switched to the Sierra flow controller, and 2% hydrogen in air was supplied using the MKS controller, with a total flow rate of 9 SLPM. A few test concentrations were applied; these are annotated in Figure 47. The maximum hydrogen concentration of 0.20% corresponds to a helium concentration of approximately 56.3%; at 0.00% hydrogen, the helium concentration is that of the mixed helium cylinder, 62.6%. It was observed that with these high concentrations of helium, the hydrogen sensitivity seemed to be significantly higher; note that both sensors BHF403 and BHF404 come close to their saturation values with 0.2% hydrogen; compare this to the amplitude values in Figure 45.

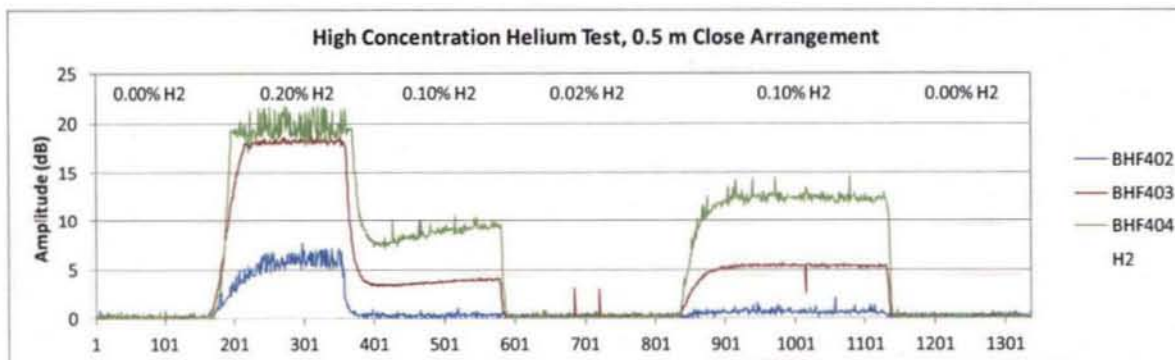


Figure 47. High helium concentration test results

Since it was not expected that the thin film would respond to helium, a hypothesis was developed that the increased sensitivity might be due to the lower oxygen concentration. To test this hypothesis, the sensors were exposed to 2% hydrogen in nitrogen, which was supplied using the Sierra S/N 106456 controller. After the sensors saturated, the flow was continued to ensure the oxygen in the test enclosures was displaced. The flow was then terminated, and the amplitude data was monitored. It was noted that the sensors remained saturated even after the termination of flow and the disconnection of the supply line, despite the fact that the small amount of hydrogen in each test enclosure was expected to stratify fairly quickly at the top of the enclosure. The supply line was then reconnected, and the controller was switched to breathing air at a low flow rate. The exposure to breathing air slowly returned the sensors to their background noise levels. To confirm that the effect was due to the lack of oxygen rather than the lack of gas flow, the exposure test could be performed with test gases of nitrogen and 2% hydrogen in nitrogen instead of breathing air and 2% hydrogen in air; if the lack of oxygen does not allow the sensors to recover, then the sensors should remain saturated after the first exposure to hydrogen.

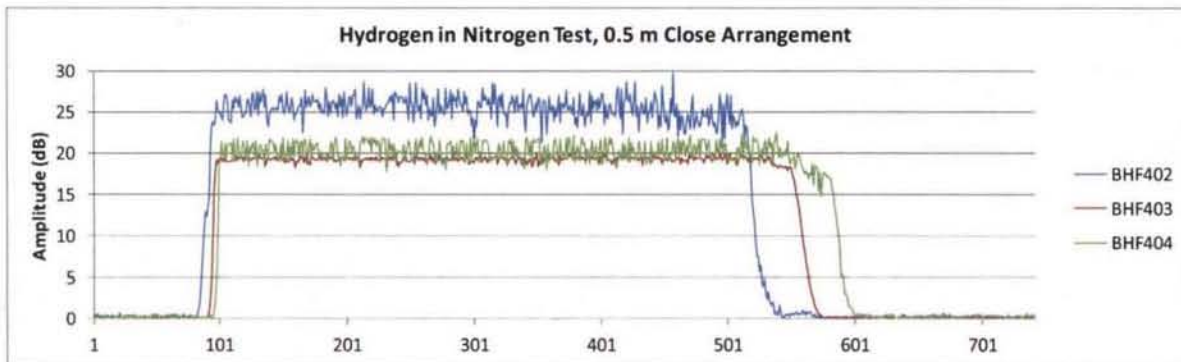


Figure 48. Hydrogen in nitrogen test results

2.6 Other Support

Also supported on this task order was the receiving and demonstration of the ASR&D Corporation wireless humidity sensor system, delivered to KSC under STTR Phase II contract NNX09CB77C, and associated NASA property management actions. Characterization testing of this system is not currently within the scope of this task order.

3. CONCLUSIONS AND RECOMMENDATIONS

3.1 Summary of Results

RF characterization of the Mnemonics-UCF SAW sensor system shows significant broadcast power outside the ISM band, both at the fundamental frequency (which was expected) and in the harmonics, which are observable above the background noise out to the fifth harmonic. The second harmonic is only 20 dB down from the fundamental. The low repetition rate of the system makes RF analysis challenging; data capture was improved through the creation of a MATLAB script to increase the query repetition rate. The use of a high-speed oscilloscope

makes single-shot characterization possible for the fundamental frequency band and the time-domain characteristics of the interrogator pulse. Near-field probe test data has been captured, but has not yet been analyzed.

When capturing data as a temperature measurement system, the relative orientations and spacing of the antenna and sensor strongly affect the stability of the measurement and the ability to capture useable data. The operating software currently has no means to determine when valid sensor data is present. Relative differences were observed in the performance of the four supplied temperature sensors. Ground plane effects may also strongly affect the performance of the sensors in some orientations. Free-space range was tested for a single sensor and found to be less than 5 m for the default integration time of the system. Stable, low-noise operation was observed with a short distance (0.5 m) between the sensor and antenna. When considered on an aggregate basis, the collected data shows a strong, fairly consistent trend in the relationship between the standard deviation of the data, taken to be the noise level, and the software's calculated correlation peak, taken to be the signal level. Initial temperature testing shows good correlation between the sensor data and measurements taken with a calibrated thermocouple readout.

When capturing data as a hydrogen measurement system, the sensors respond quickly to changes in ambient hydrogen concentration, down to levels as low as 0.1% in air. The three sensors tested had significant differences in their sensitivity to hydrogen. Sensor noise levels increase with increasing distance, though response to hydrogen was not tested at distances other than 0.5 m. Also, some hysteresis and slope was observed in the data; it is not known whether these effects are due to the sensor response or due to factors in the test setup, such as stratification of the mixed gas in the cylinders.

3.2 Conclusions

Given the RF output levels at frequencies allocated to other devices, it is not anticipated that the sensor system will be approved for use at KSC outside the EMI test chamber. Possible mitigations could include an ISM filter on the output of the interrogator, though this may significantly reduce the performance of the system by truncating the RF spectrum used by the sensors.

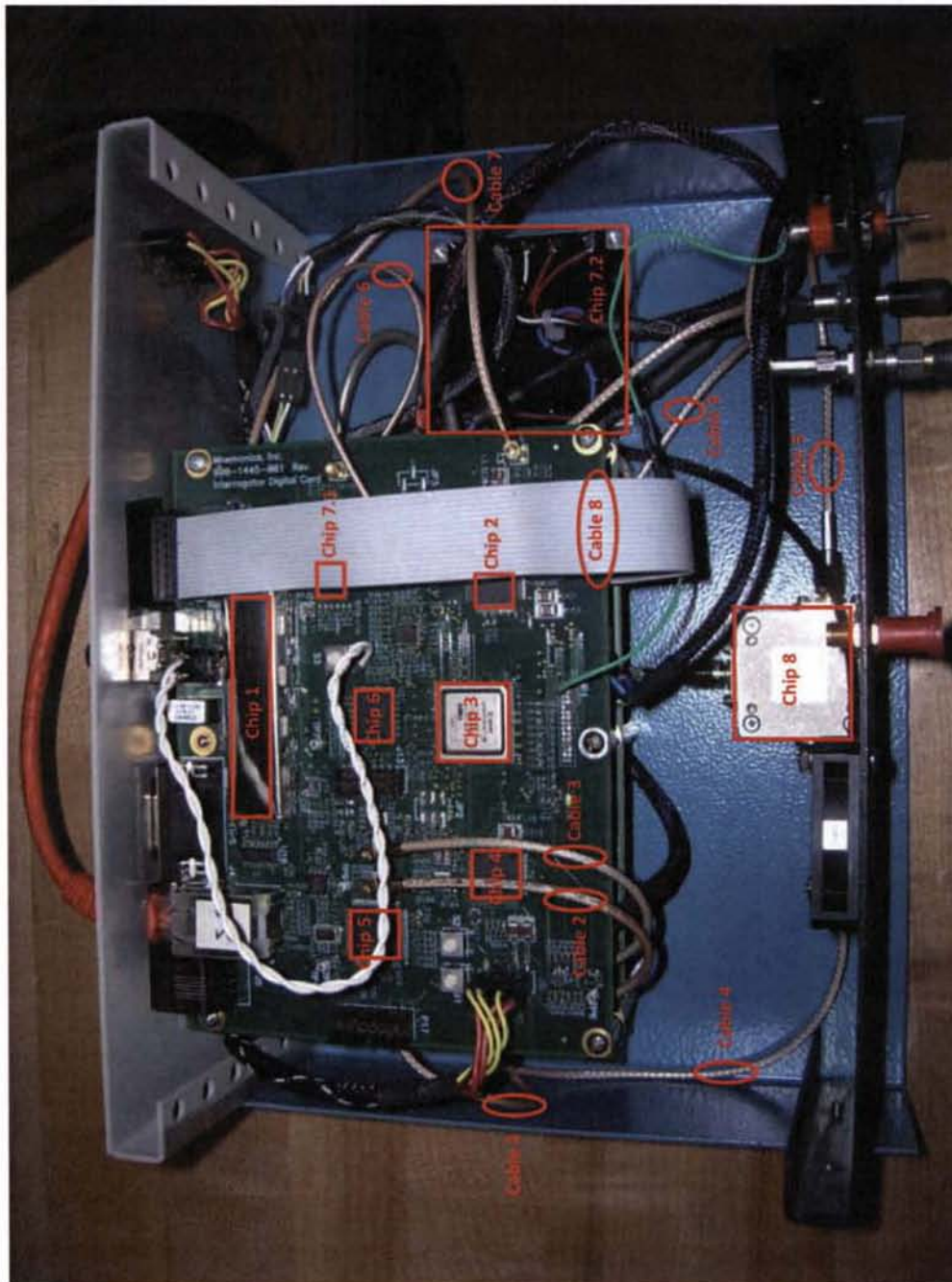
As a system, temperature can be measured with relatively small amounts of noise when the interrogator antenna and sensor are sufficiently close together, and in favorable relative orientations. The correlation peak value calculated by the software could be used to estimate the confidence interval of a given measurement. System accuracy is yet to be determined, and will require testing with more sensors over wider ranges of temperature, but initial results show good tracking of the actual temperature profile. Hydrogen can be sensed at fairly low concentrations, well below the 4% lower flammability limit for hydrogen in air. Again, system accuracy is yet to be determined, and each sensor shows different sensitivity.

3.3 Recommendations

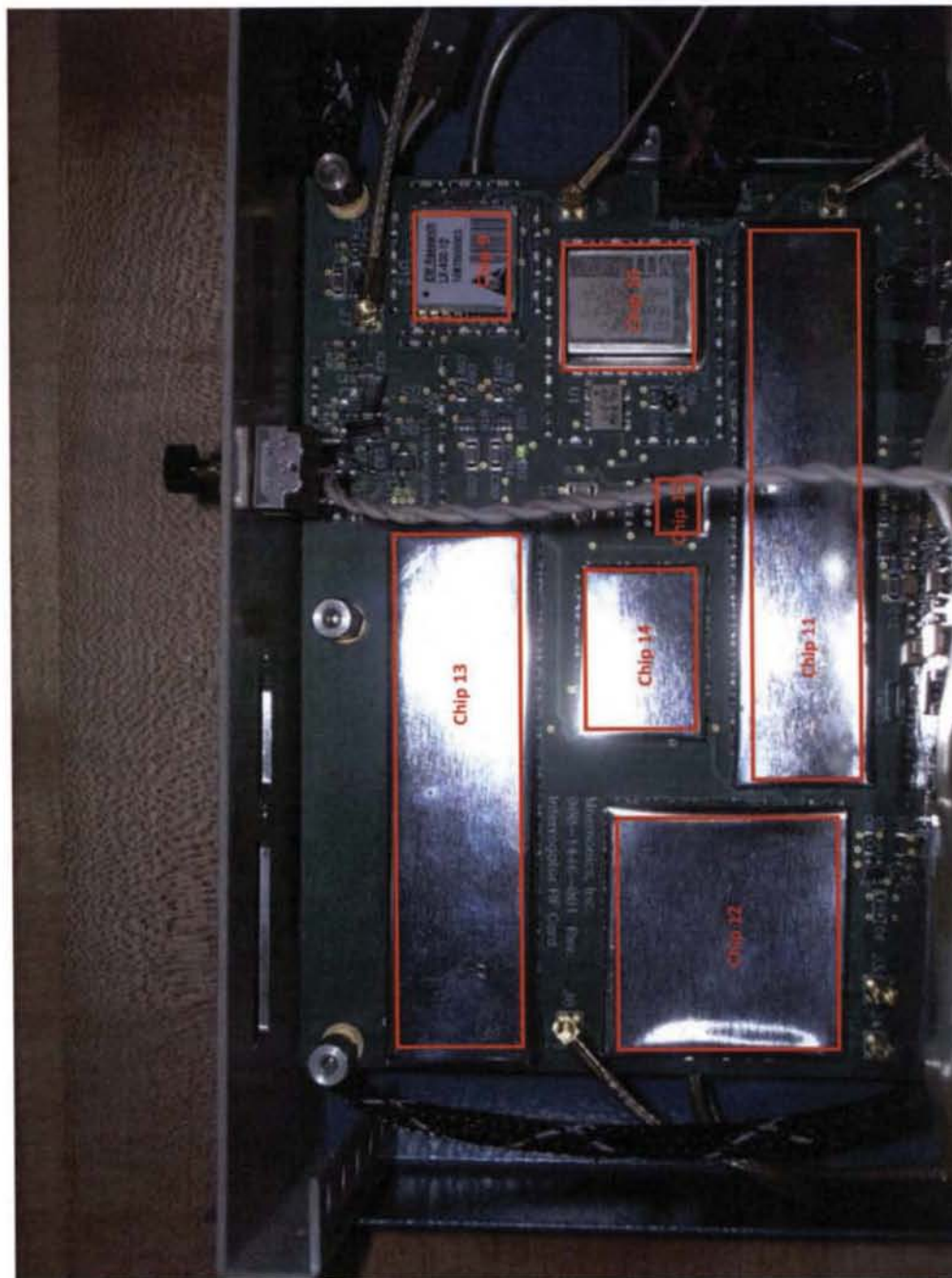
Future testing should include wider ranges of temperature to characterize accuracy performance for the temperature sensors. Temperature measurement performance should also be tested with multiple sensors. The trend between sensor noise and correlation peak should be improved by the addition of more data, to determine whether this would be a reasonable predictor of the accuracy of sensor measurements. The effects of integration time on sensor noise and accuracy should be examined. For the hydrogen sensors, concentration tests should be repeated to determine whether the sensors can be reliably calibrated, which would be necessary for determining accuracy. Hydrogen sensitivity could be tested with more confidence at low levels by procuring a mixed gas cylinder with a lower concentration of hydrogen in air, such as 0.4%; this could be used for both the exposure test and the concentration test, where it could be mixed to even lower concentrations. The hydrogen measurement software would also benefit from the addition of a timestamp to the recorded data files, which would allow the temporal correlation of the input profile and the measured data. The signals observed in the quiet EMI chamber should be identified, which may be possible by terminating the input of the spectrum analyzer and observing whether a nearby GSM cell phone may be detected.

APPENDIX A. NEAR-FIELD PROBE TEST RESULTS

Following is the data collected during near-field probe testing. Spectrum captures are given for each of the internal components indicated in the images.



Upper board and cabling



Lower board



Test setup; pre-amplifier is shown at the top; near-field probe and interrogator are at lower right

Chip designations (where available); for cables, see image

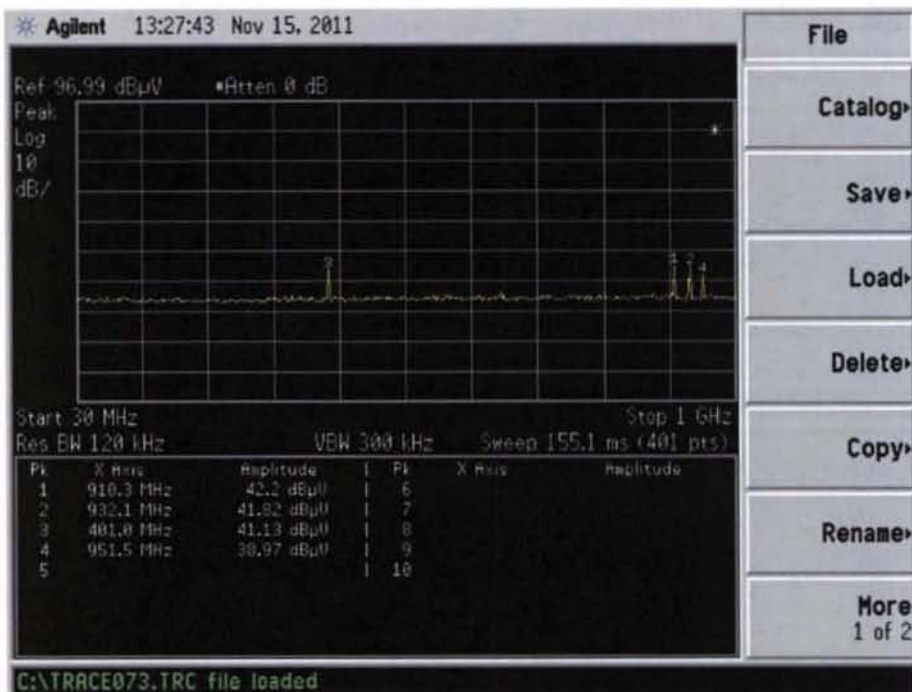
Chip 1	?
Chip 2	U18
Chip 3	U14?
Chip 4	?
Chip 5	U13
Chip 6	U27
Chip 7.1	?
Chip 7.2	DC/DC Converter?
Chip 8	RF Combiner?
Chip 9	U12
Chip 10	U13
Chip 11	?
Chip 12	?
Chip 13	?
Chip 14	?
Chip 15	?

Equipment Used:

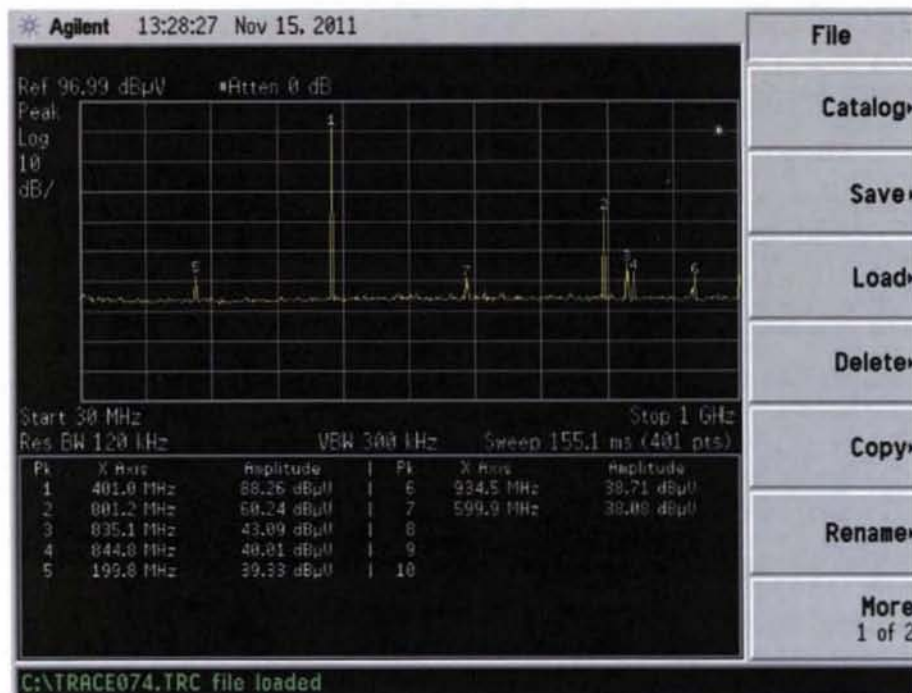
Agilent E7405A Spectrum Analyzer
Agilent 11940A Near-field Probe
HP 8447F pre-amp
09-09-407 60" cable
08-08-801 39.7" cable

Equipment Settings:

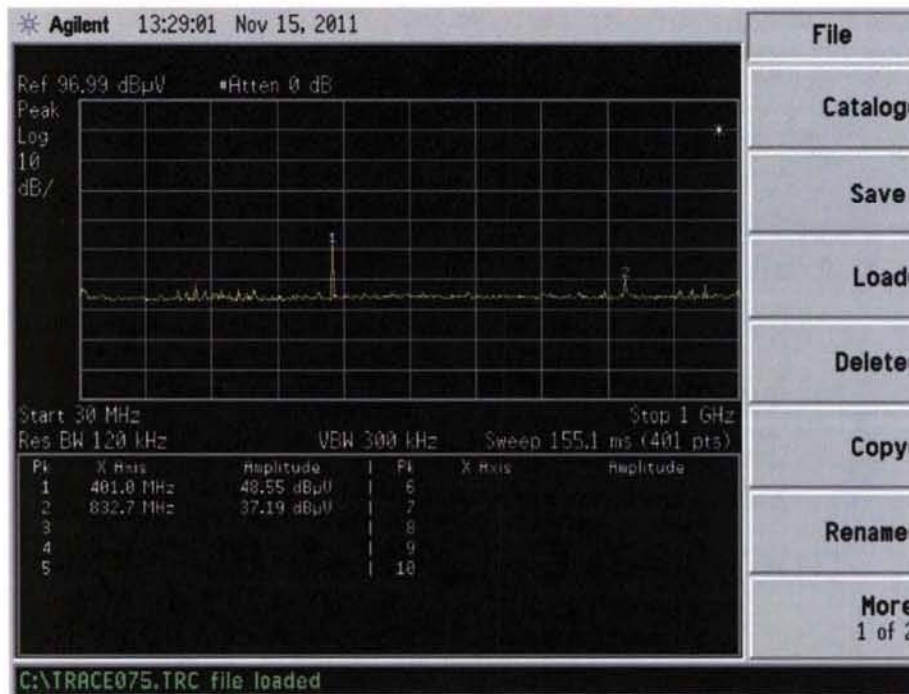
30 MHz – 1 GHz Span
RBW 120 kHz, VBW 300 kHz
AC Coupled
Max Hold for 2.5 min



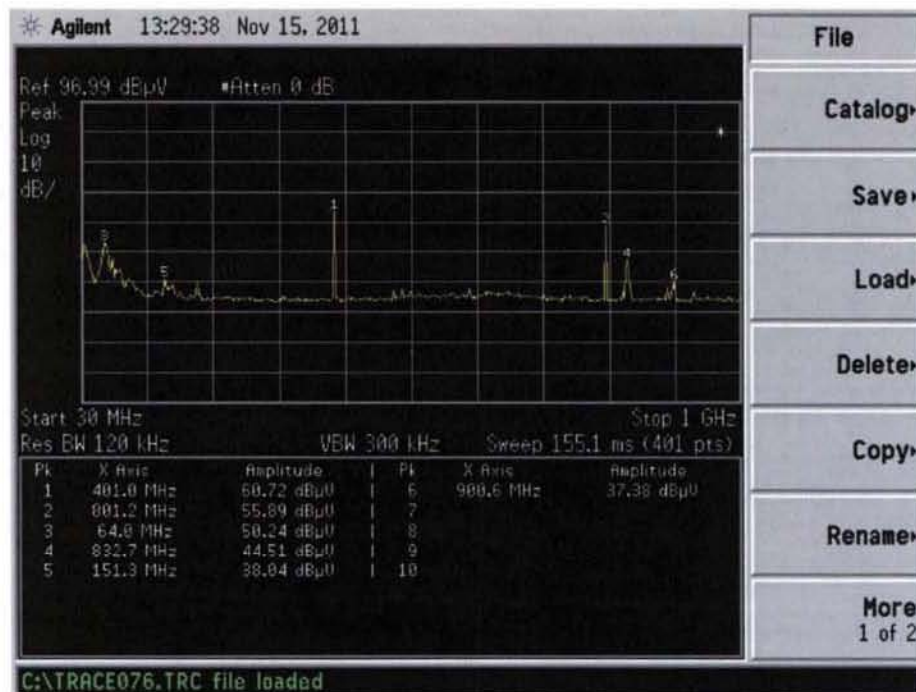
Chip 1



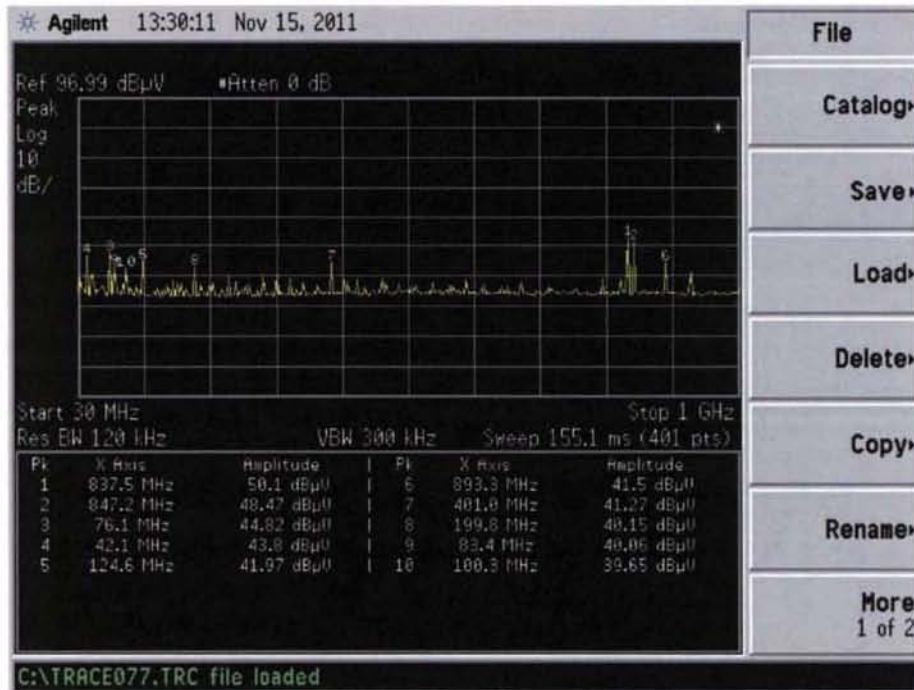
Chip 2



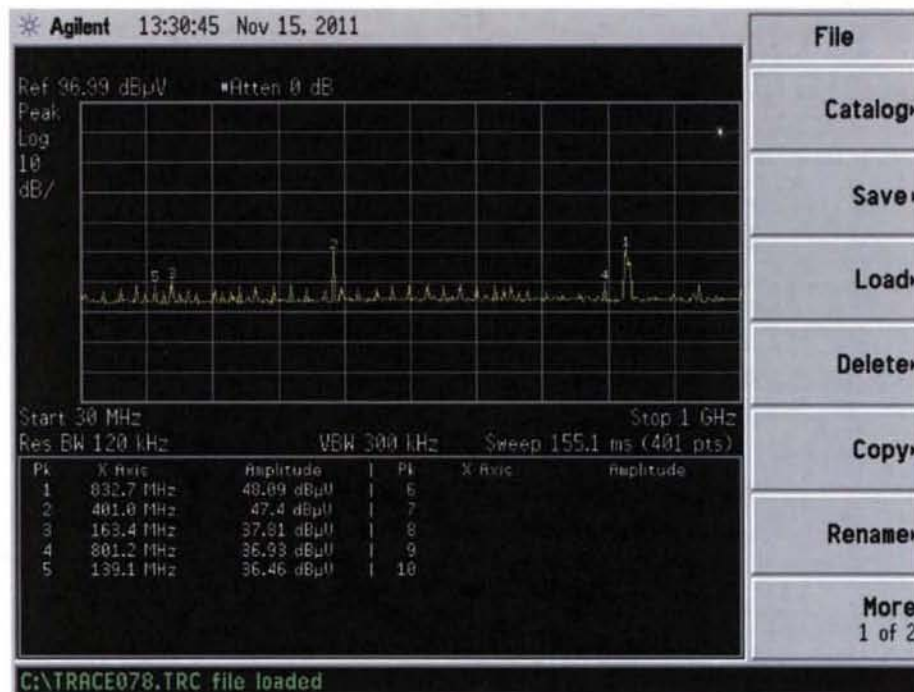
Chip 3



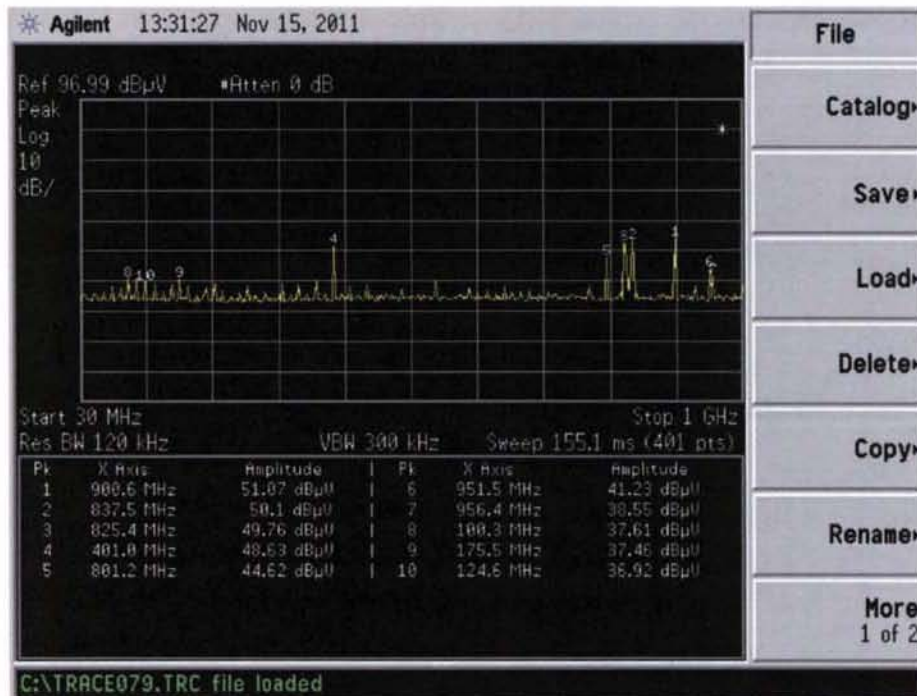
Chip 4



Chip 5



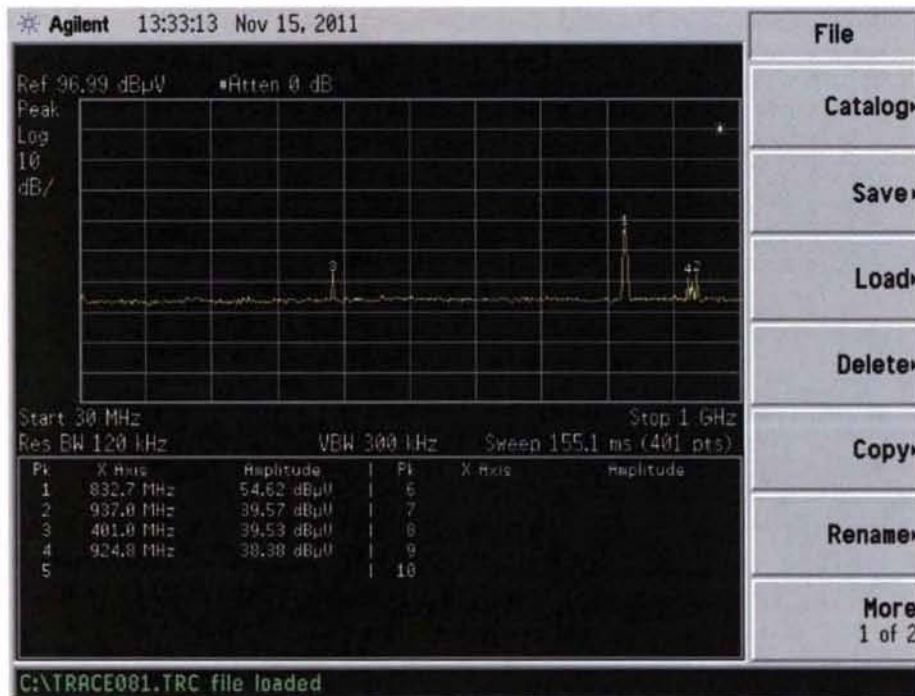
Chip 6



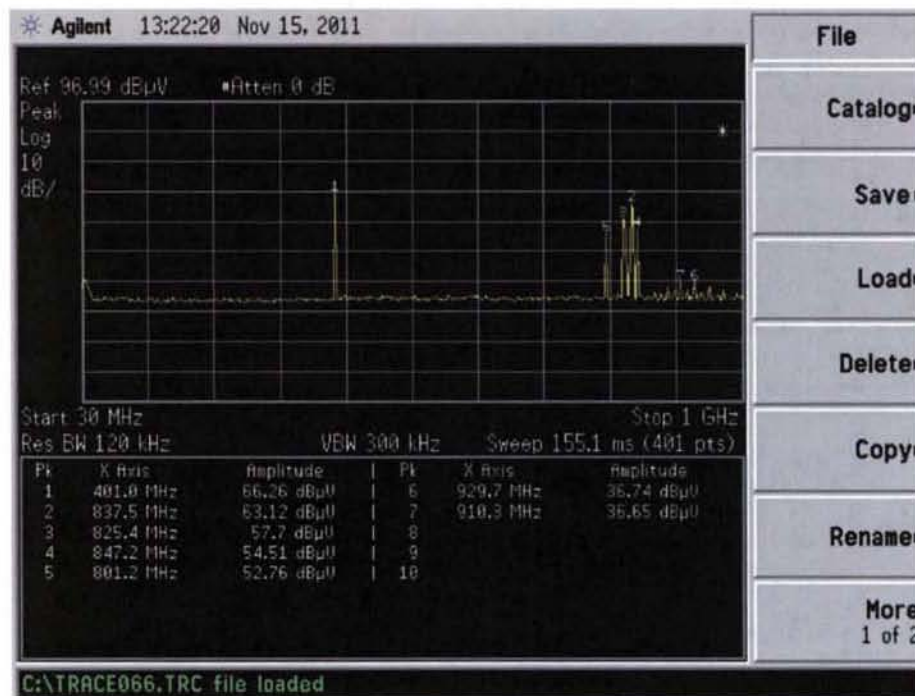
Chip 7.1



Chip 7.2



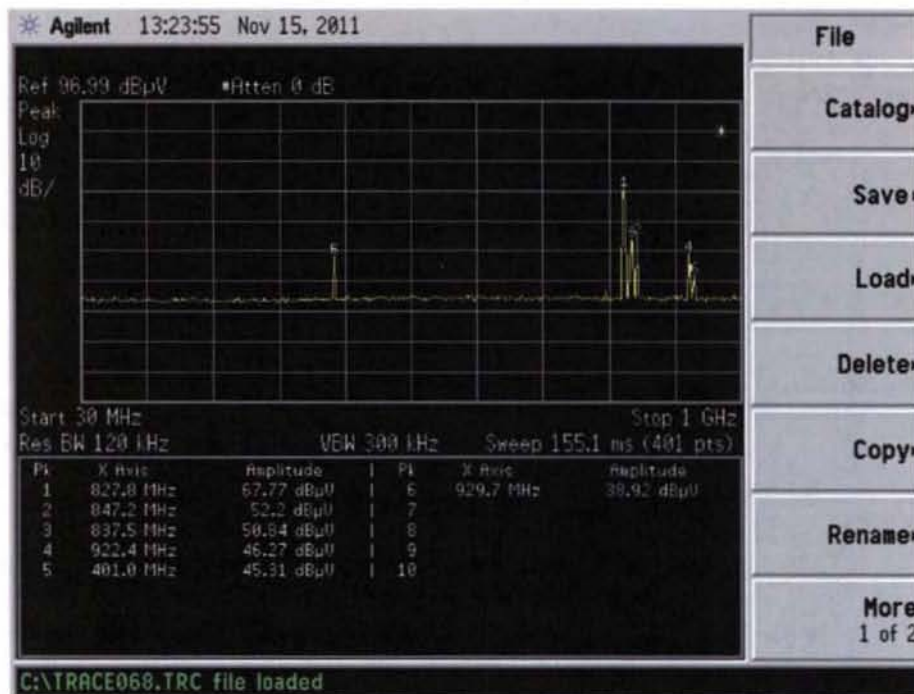
Chip 8



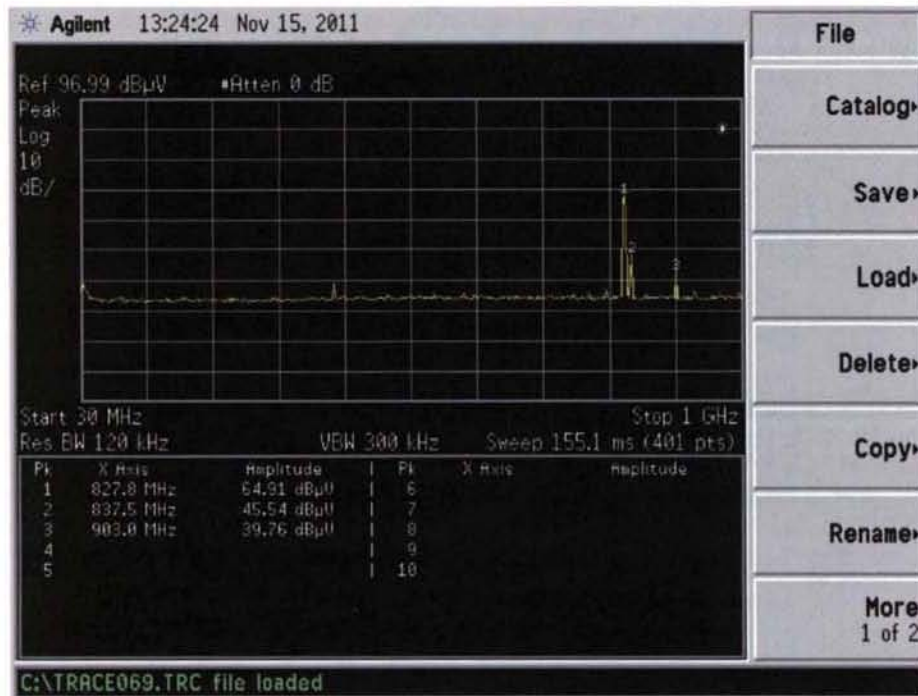
Chip 9



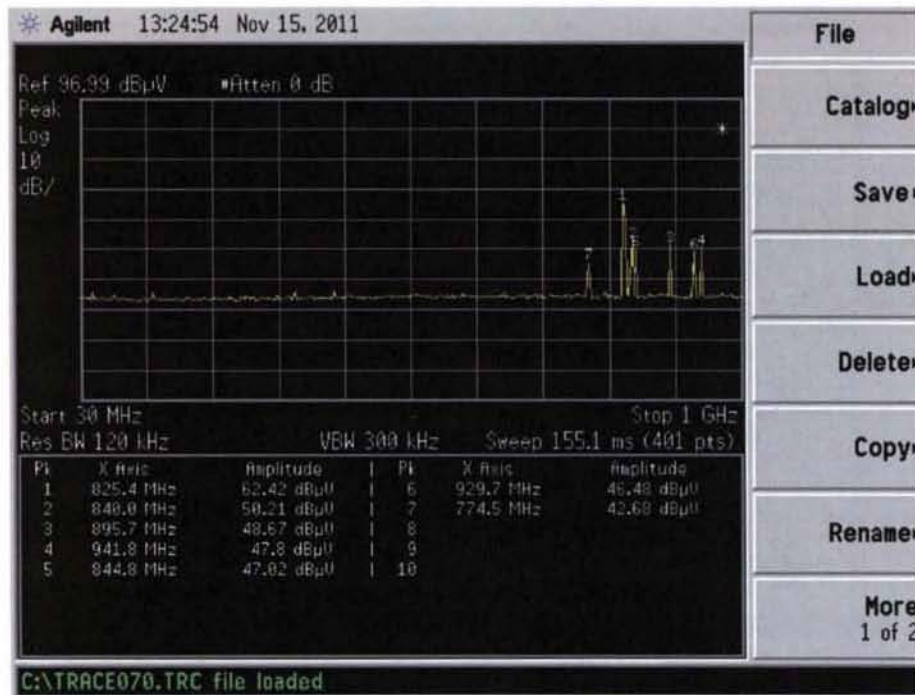
Chip 10



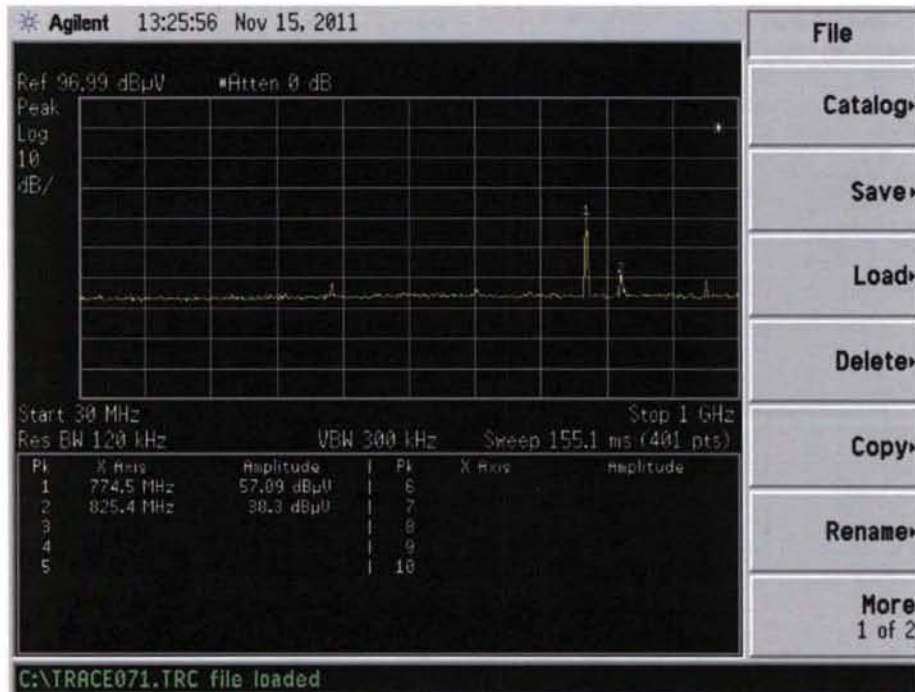
Chip 11



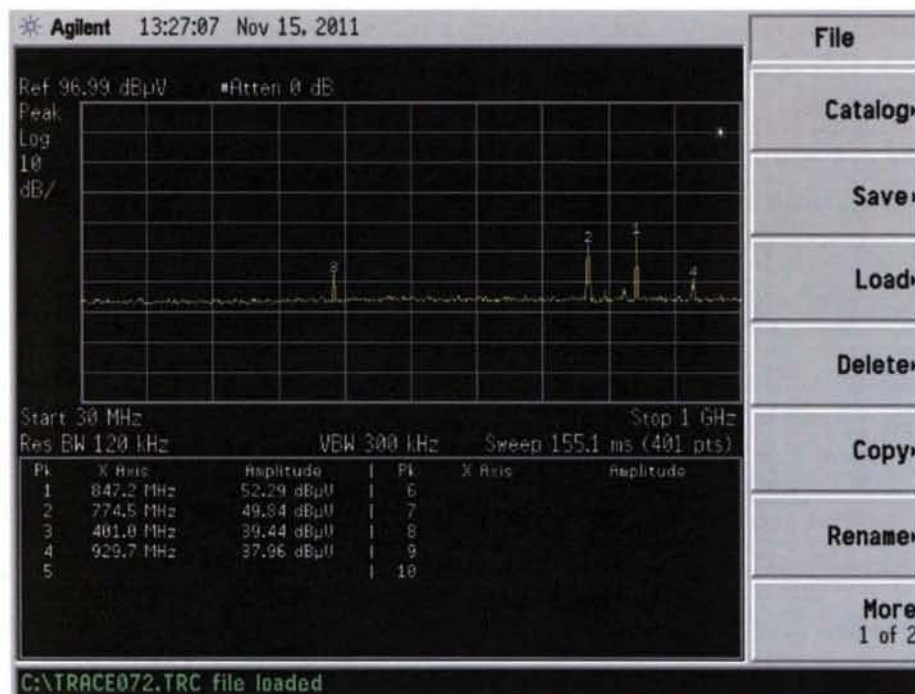
Chip 12



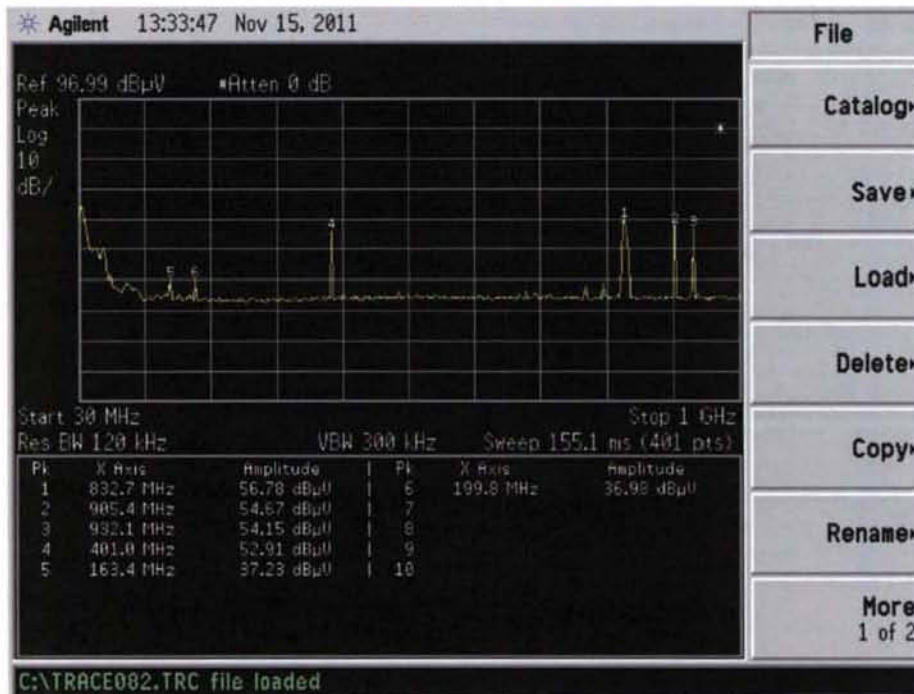
Chip 13



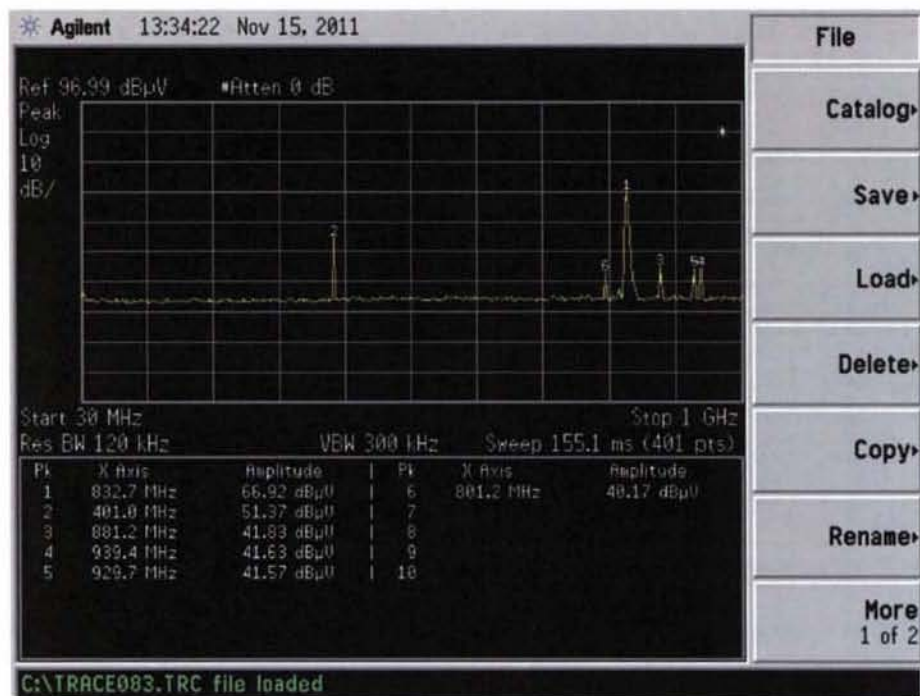
Chip 14



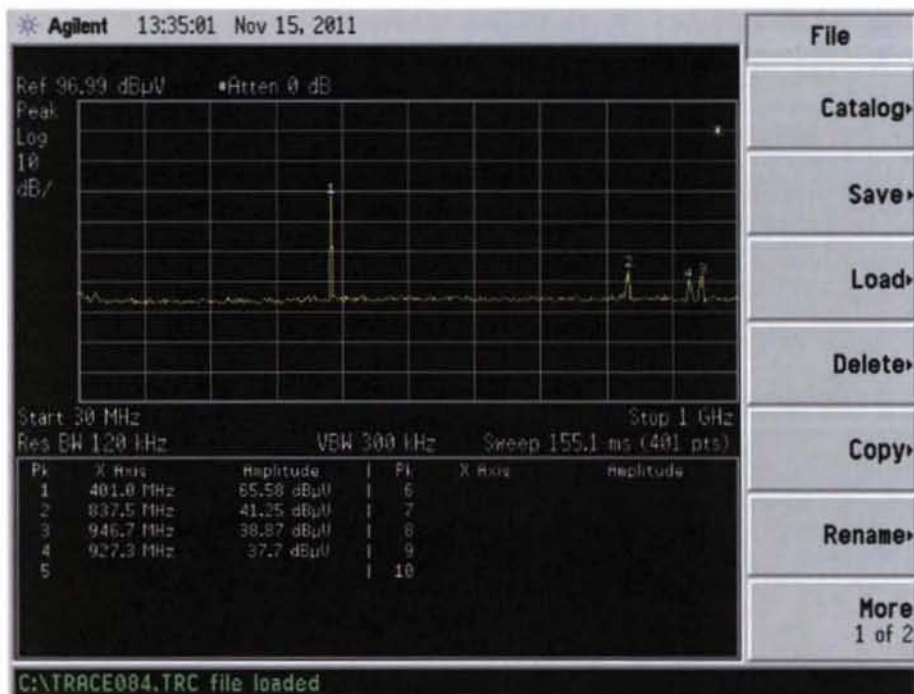
Chip 15



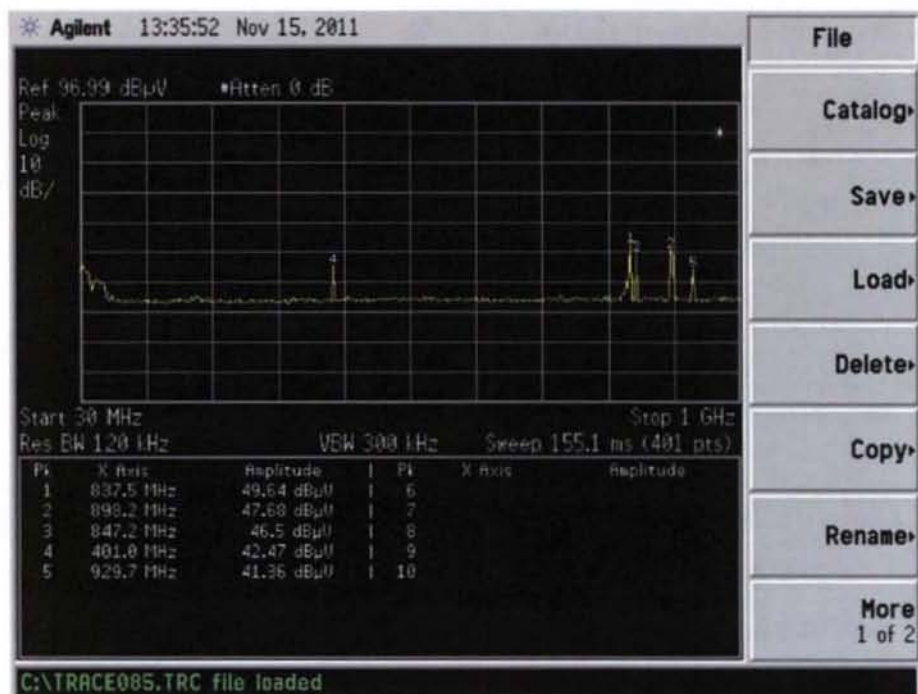
Cable 1



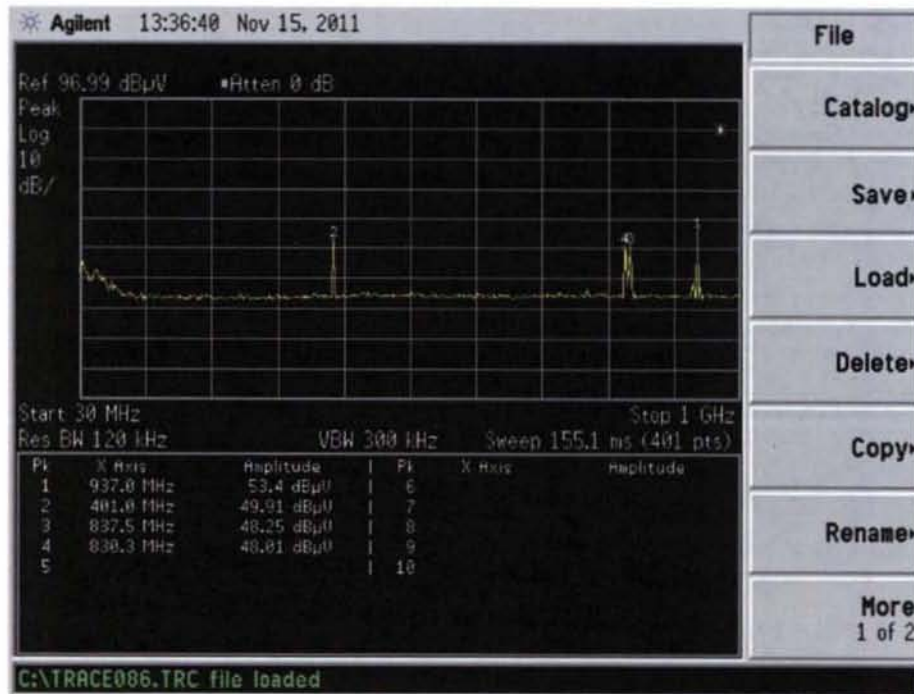
Cables 2 & 3



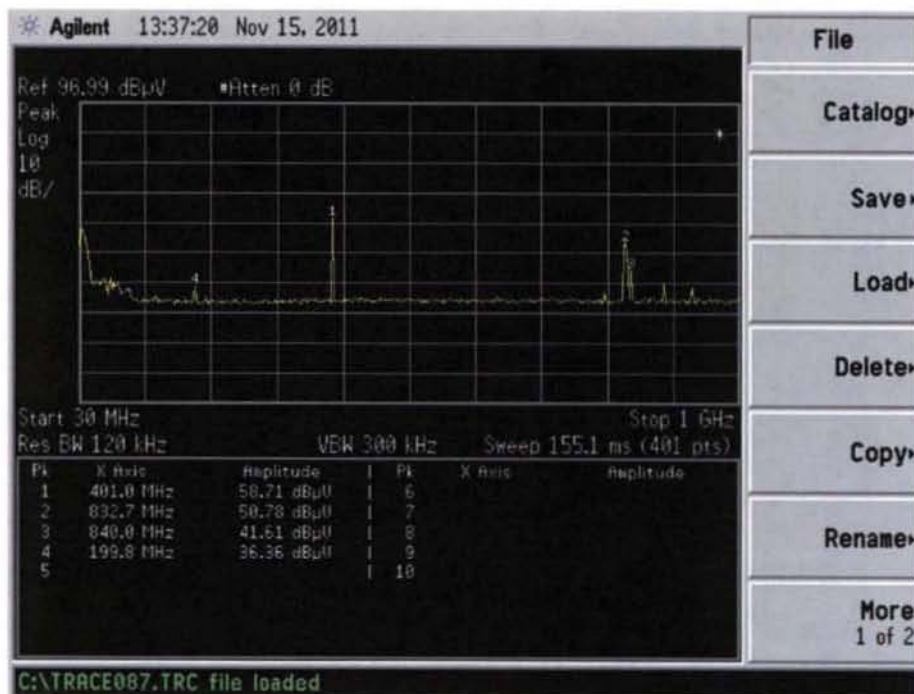
Cable 4



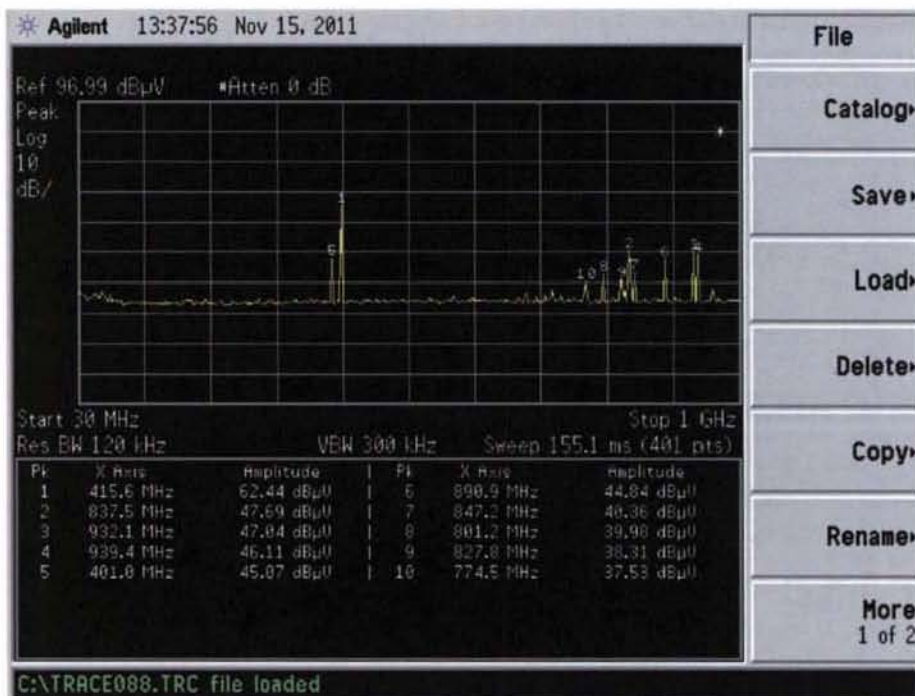
Cable 5



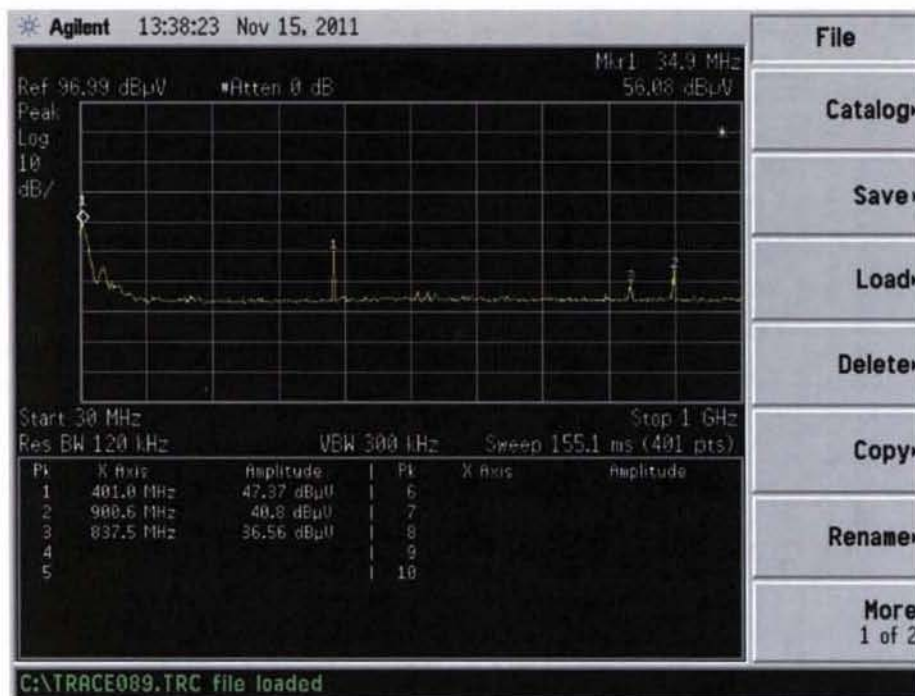
Cable 6



Cable 7



Cable 8



Cable 9

APPENDIX B. DATA SHEETS

Following is the data summary sheet from the temperature testing herein, representing 81 individual data files (over 42,000 points), which are stored separately.

File	Sensor	Orientation	Distance (m)	Test	Notes	Temperature (°C)		Exhaust Fans	Location	Rows	Temperature (°C)		Residual (21-point median)		Correlation Peak	
						Start	Stop				Average	Std Dev	Average	Std Dev	Average (dB)	Std Dev (dB)
SAW Data 2011-09-27 13:51:04.txt	NS401R	1: Vertical	0.25	Range/stability				TRUE	Table	620	25.42472659	0.114165774	0.053021002	0.247837008		
SAW Data 2011-09-27 14:28:06.txt	NS401R	2: Horizontal	0.25	Range/stability				TRUE	Table	605	19.99301119	0.2119651864	-2.04024834	21.12822363		
SAW Data 2011-09-27 15:15:38.txt	NS401R	3: Rotated Vertical	0.25	Range/stability				TRUE	Table	582	25.64671384	0.2517063388	-0.061624785	0.236042116		
SAW Data 2011-09-27 15:51:03.txt	NS401R	4: Rotated Horizontal	0.25	Range/stability				TRUE	Table	645	23.8000124	0.188747663	-0.008562112	0.135548697		
SAW Data 2011-09-27 16:30:52.txt	NS401R	1: Vertical	0.5	Range/stability	Added correlation peak in dB, but lost seconds.			TRUE	Table	534	24.32036830	0.05359166	-0.0038449	0.102123392	72.08125516	0.04366926
SAW Data 2011-09-27 16:30:52.txt	NS401R	1: Vertical	0.5	Range/stability	Repeat next day to verify correlation peak functionality.			TRUE	Table	611	24.31216253	0.09410679	-0.00372623	0.087639893	72.09014098	0.034010921
SAW Data 2011-09-27 16:30:52.txt	NS401R	2: Horizontal	0.5	Range/stability				TRUE	Table	1063	24.4834275	0.1438251591	-0.75237473	14.23176665	38.11148005	0.240661325
SAW Data 2011-09-27 16:30:52.txt	NS401R	3: Rotated Vertical	0.5	Range/stability				TRUE	Table	274	24.38497802	0.097087776	-0.01342857	0.094965761	72.17648718	0.028651314
SAW Data 2011-09-27 16:30:52.txt	NS401R	4: Rotated Horizontal	0.5	Range/stability				TRUE	Table	312	23.81666881	0.092737318	-0.029241158	0.300428838	58.75350804	0.12119947
SAW Data 2011-09-27 16:30:52.txt	NS401R	1: Vertical	0.75	Range/stability				TRUE	Table	285	24.08515493	0.096493453	-0.006735915	0.091936512	68.47215141	0.048237578
SAW Data 2011-09-27 16:30:52.txt	NS401R	2: Horizontal	0.75	Range/stability				TRUE	Table	495	-9.82602267	57.88606595	6.036251012	57.6592758	32.14439879	1.45603092
SAW Data 2011-09-27 16:30:52.txt	NS401R	3: Rotated Vertical	0.75	Range/stability				TRUE	Table	268	24.12127715	0.096819526	-0.001962547	0.083298666	69.09417603	0.053178898
SAW Data 2011-09-27 16:30:52.txt	NS401R	4: Rotated Horizontal	0.75	Range/stability				TRUE	Table	357	23.61545787	0.058856206	-0.12602809	0.645692745	53.78781742	0.209205035
SAW Data 2011-09-27 16:30:52.txt	NS401R	5: Flat Incline	0.75	Range/stability				TRUE	Table	273	18.83683824	18.98455798	-3.500830882	18.87323206	37.89798529	1.79007862
SAW Data 2011-09-27 16:30:52.txt	NS401R	6: Flat Perpendicular	0.75	Range/stability				TRUE	Table	451	-8.308531111	53.7371796	2.473844444	54.44036563	32.87587111	1.415100853
SAW Data 2011-09-27 16:30:52.txt	NS401R	1: Vertical	1	Range/stability				TRUE	Table	292	23.51902199	0.34029663	-0.043611684	0.239416079	64.30876976	0.061634786
SAW Data 2011-09-27 16:30:52.txt	NS401R	2: Horizontal	1	Range/stability				TRUE	Table	393	-1.448857143	58.59791447	1.706219388	56.89453872	32.59671173	1.45130534
SAW Data 2011-09-27 16:30:52.txt	NS401R	3: Rotated Vertical	1	Range/stability				TRUE	Table	332	23.54883082	0.152006659	-0.0398429	0.192172822	64.68635952	0.064422804
SAW Data 2011-09-27 16:30:52.txt	NS401R	4: Rotated Horizontal	1	Range/stability				TRUE	Table	308	23.69815635	1.257851907	-0.127710098	1.217939983	48.10444951	0.410088407
SAW Data 2011-09-27 16:30:52.txt	NS401R	5: Flat Incline	1	Range/stability				TRUE	Table	316	10.36121905	47.44967905	8.965830995	47.26379408	33.66790784	1.395004766
SAW Data 2011-09-27 16:30:52.txt	NS401R	6: Flat Perpendicular	1	Range/stability				TRUE	Table	520	-4.591714816	58.7276358	6.199171884	58.0877105	32.0245087	1.395004766
SAW Data 2011-09-27 16:30:52.txt	NS401R	1: Vertical	0.25	Range/stability				TRUE	Table	341	23.91764706	1.160566337	-0.09535824	1.136860004	40.21919706	0.354298267
SAW Data 2011-09-27 16:30:52.txt	NS401R	2: Horizontal	0.25	Range/stability				TRUE	Table	320	23.81270219	0.832338271	-0.33584126	0.781317131	40.56337931	0.2898886
SAW Data 2011-09-27 16:30:52.txt	NS401R	3: Rotated Vertical	0.25	Range/stability				TRUE	Table	318	23.99376079	2.041987371	-0.146277603	2.016572356	44.18775079	0.64252872
SAW Data 2011-09-27 16:30:52.txt	NS401R	4: Rotated Horizontal	0.25	Range/stability				TRUE	Table	762	16.31105913	33.3049348	-5.291920041	33.08736187	35.67306813	1.410643559
SAW Data 2011-09-27 16:30:52.txt	NS401R	1: Vertical	0.25	Range/stability	Repeat with correlation peak functionality.			TRUE	Table	311	24.51893548	0.288060127	-0.019470968	0.229243114	73.79739677	0.073037154
SAW Data 2011-09-27 16:30:52.txt	NS401R	2: Horizontal	0.25	Range/stability				TRUE	Table	289	17.78604097	28.7351483	-5.377625	28.59469661	37.13689543	1.364251894
SAW Data 2011-09-27 16:30:52.txt	NS401R	3: Rotated Vertical	0.25	Range/stability				TRUE	Table	293	24.74587329	0.738576972	-0.032184932	0.216055776	73.88864726	0.057100763
SAW Data 2011-09-27 16:30:52.txt	NS401R	4: Rotated Horizontal	0.25	Range/stability				TRUE	Table	285	23.87126761	0.153680841	-0.018616197	0.150344706	65.10253873	0.063433295
SAW Data 2011-09-27 16:30:52.txt	NS401R	5: Flat Incline	0.25	Range/stability				TRUE	Table	298	22.11603367	0.894780903	-0.041407407	0.256900655	74.26085563	0.238510037
SAW Data 2011-09-27 16:30:52.txt	NS401R	6: Flat Perpendicular	0.25	Range/stability				TRUE	Table	299	28.67818792	0.842761849	0.075436242	1.185833985	54.69873064	0.238510037
SAW Data 2011-09-27 16:30:52.txt	NS401R	1: Vertical	0.25	Range/stability				TRUE	Table	298	25.19600943	0.173984959	0.003905724	0.169517512	69.22565772	0.02720932
SAW Data 2011-09-27 16:30:52.txt	NS401R	2: Horizontal	0.25	Range/stability				TRUE	Table	273	25.277625	0.070243547	0.038889706	0.649941702	53.31743382	0.172150848
SAW Data 2011-09-27 16:30:52.txt	NS401R	3: Rotated Vertical	0.25	Range/stability				TRUE	Table	298	26.13785859	1.481480789	0.23730193	1.653615985	49.45688136	0.25245317
SAW Data 2011-09-27 16:30:52.txt	NS401R	4: Rotated Horizontal	0.25	Range/stability				TRUE	Table	330	24.96277204	0.104064208	0.009660605	0.10397538	71.81291489	0.045624994
SAW Data 2011-09-27 16:30:52.txt	NS401R	5: Flat Incline	0.5	Range/stability				TRUE	Table	350	24.81187966	0.649468892	-0.015510315	0.391230333	59.2582894	0.21332379
SAW Data 2011-09-27 16:30:52.txt	NS401R	6: Flat Perpendicular	0.5	Range/stability				TRUE	Table	361	26.73890278	0.48501212	-0.002111111	0.480795493	72.97194167	0.042757129
SAW Data 2011-09-27 16:30:52.txt	NS401R	1: Vertical	0.5	Range/stability				TRUE	Table	717	23.22727626	0.84938356	0.024121508	0.941690152	53.05921369	0.16656085
SAW Data 2011-09-27 16:30:52.txt	NS401R	2: Horizontal	0.5	Range/stability				TRUE	Table	745	26.7957392	0.754600651	0.014032558	0.66423008	54.3018871	0.252726447
SAW Data 2011-09-27 16:30:52.txt	NS401R	3: Rotated Vertical	0.75	Range/stability				TRUE	Table	2157	18.38978154	3.860121412	0.279324675	4.038837967	47.15324536	0.315291157
SAW Data 2011-09-27 16:30:52.txt	NS401R	4: Rotated Horizontal	0.75	Range/stability				TRUE	Table	284	29.62895406	0.253003941	0.041187779	0.235300042	73.29104594	0.030187852
SAW Data 2011-09-27 16:30:52.txt	NS401R	5: Flat Incline	0.75	Range/stability				TRUE	Table	373	25.19426075	0.158429776	0.00775	0.149341247	67.09383871	0.045837587
SAW Data 2011-09-27 16:30:52.txt	NS401R	6: Flat Perpendicular	0.75	Range/stability				TRUE	Table	285	28.63623944	0.641382054	0.018887324	0.676546156	73.60568662	0.021075017
SAW Data 2011-09-27 16:30:52.txt	NS401R	1: Vertical	0.75	Range/stability				TRUE	Table	363	22.4519558	0.360812116	0.033964088	0.342979694	63.54331768	0.119385018
SAW Data 2011-09-27 16:30:52.txt	NS401R	2: Horizontal	0.75	Range/stability				TRUE	Table	760	20.29211331	0.292279672	0.028710145	0.288670431	54.72339657	0.130915478
SAW Data 2011-09-27 16:30:52.txt	NS401R	3: Rotated Vertical	0.75	Range/stability				TRUE	Table	358	22.67236134	1.840082462	0.071963585	1.19701284	51.55857703	0.187954701
SAW Data 2011-09-27 16:30:52.txt	NS401R	4: Rotated Horizontal	0.75	Range/stability				TRUE	Table	358	24.76250998	1.87132017	-0.11510084	1.804417014	47.08087395	0.31392887
SAW Data 2011-09-27 16:30:52.txt	NS401R	5: Flat Incline	0.75	Range/stability				TRUE	Table	336	27.526209	0.280954696	-0.02660597	0.27876499	73.70961194	0.029770356
SAW Data 2011-09-27 16:30:52.txt	NS401R	6: Flat Perpendicular	0.75	Range/stability				TRUE	Table	338	20.18833234	0.758498954	-0.00943234	0.737457825	51.3402997	0.250881272
SAW Data 2011-09-27 16:30:52.txt	NS401R	1: Vertical	1	Range/stability				TRUE	Table	389	24.44199742	0.33292581	-0.04270732	0.313887844	71.20662113	0.04866677
SAW Data 2011-09-27 16:30:52.txt	NS401R	2: Horizontal	1	Range/stability				TRUE	Table	277	20.75972826	0.55122419	0.056905797	0.335175442	63.36806966	0.077932483
SAW Data 2011-09-27 16:30:52.txt	NS401R	3: Rotated Vertical	1	Range/stability				TRUE	Table	650	25.0006634	0.60070538	-0.065594388	0.597203635	52.96111402	0.175067311
SAW Data 2011-09-27 16:30:52.txt	NS401R	4: Rotated Horizontal	1	Range/stability				TRUE	Table	406	22.7696	3.355107856	-0.147766467	3.294120856	40.70119012	0.666790918
SAW Data 2011-09-27 16:30:52.txt	NS401R	5: Flat Incline	1	Range/stability				TRUE	Table	322	17.14851402	0.254153953	-0.022641745	0.248507795	70.8737539	0.058611566
SAW Data 2011-09-27 16:30:52.txt	NS401R	6: Flat Perpendicular	1	Range/stability				TRUE	Table	923	18.6289577	1.165848707	0.251075792	3.16491917	47.39640855	0.467390887
SAW Data 2011-09-27 16:30:52.txt	NS401R	1: Vertical	1	Range/stability				TRUE	Table	1585	18.25395833	1.486627293	-0.009412576	0.237709306	69.90680886	0.047428101
SAW Data 2011-09-27 16:30:52.txt	NS401R	2: Horizontal	1	Range/stability				TRUE	Table	430	18.63766434	1.529993324	0.107876457	1.237779502	54.57328904	0.216592009

File	Sensor	Orientation	Distance (m)	Test	Notes	Temperature (°C)	Exhaust	Location	Rows	Average (°C)	Std Dev (°C)	Residual (21-point median)	Average (dB)	Std Dev (dB)	Correlation Peak
SAW Data 2011-10-05 16:03:22.txt	NS403R	5: Flat In-line	1	Range/stability		23.1	23.3	Table	274	28.2525348	11.48862814	1.485164335	42.56420513	0.666061775	
SAW Data 2011-10-05 16:20:53.txt	NS403R	6: Flat Perpendicular	1	Range/stability		23.3	23.4	Table	1950	-2.388195485	58.11558843	0.328156491	33.15060318	1.384540142	
SAW Data 2011-10-06 15:12:53.txt	NS401R	1: Vertical	6.55	Range/stability	Corner to corner.	23.4	23.5	Tripo	366	14.28738356	57.73208957	-1.4081551	32.78838452	1.133726387	
SAW Data 2011-10-06 16:39:17.txt	NS401R	1: Vertical	6	Range/stability		23.6	23.4	Tripo	967	13.15334658	42.77212463	-0.4885583	34.46124327	1.21933671	
SAW Data 2011-10-06 17:51:40.txt	NS401R	1: Vertical	5	Range/stability		23.4	23.3	Tripo	387	-8.413531679	61.94454617	8.581779181	32.84125955	1.169487539	
SAW Data 2011-10-07 10:17:12.txt	NS401R	1: Vertical	4	Range/stability		23.2	23.1	Tripo	799	21.047140583	10.20388891	-0.4327171003	38.64418609	1.090440722	
SAW Data 2011-10-07 11:03:43.txt	NS401R	1: Vertical	3	Range/stability		23.1	23.3	Tripo	894	25.28935787	6.204173513	-0.376938845	40.77924915	0.814676796	
SAW Data 2011-10-07 11:56:55.txt	NS401R	1: Vertical	2.5	Range/stability		23.2	23.1	Tripo	463	25.44919697	2.66028152	-0.09679221	43.18740701	0.612943968	
SAW Data 2011-10-07 12:28:45.txt	NS401R	1: Vertical	2	Range/stability		23.3	23.1	Tripo	1187	24.55265599	1.67944434	-0.06216732	45.76545025	0.493772213	
SAW Data 2011-10-07 13:39:43.txt	NS401R	1: Vertical	1.5	Range/stability		23.2	23.4	Tripo	517	22.9341938	1.106488158	-0.305151163	53.08113372	0.200540482	
SAW Data 2011-10-07 14:13:56.txt	NS401R	1: Vertical	1	Range/stability		23.4	23.4	Tripo	644	23.5422846	0.106527968	-0.08579938	48.6223141	0.184488946	
SAW Data 2011-10-07 15:02:38.txt	NS401R	1: Vertical	0.5	Range/stability		23.4	23.3	Tripo	1849	23.93889069	0.117137432	-0.013498918	56.52789889	0.052674885	
SAW Data 2011-10-07 16:49:32.txt	NS401R	1: Vertical	1	Range/stability	Repeat to ensure no baseline shift.	23.4	23.3	Table	577	23.44966146	0.534921018	-0.125592014	56.49888021	0.1668771	
SAW Data 2011-10-12 13:08:14.txt	NS404	1: Horizontal	1	Range/stability		22.5	22.4	Table	413	30.2971966	0.68457757	0.18482767	64.81487379	0.059482223	
SAW Data 2011-10-12 13:41:39.txt	NS404	2: Horizontal	1	Range/stability		22.4	22.4	Table	281	31.98131071	69.32769036	-0.325585714	71.32300126	1.44257943	
SAW Data 2011-10-12 13:59:37.txt	NS404	3: Rotated Vertical	1	Range/stability		22.4	22.5	Table	321	32.359625	0.222332287	-0.018771875	61.45573375	0.086043919	
SAW Data 2011-10-12 14:19:45.txt	NS404	4: Rotated Horizontal	1	Range/stability		22.5	22.4	Table	514	27.50284795	1.759779925	0.118758285	1.768810764	0.389633811	
SAW Data 2011-10-12 14:50:46.txt	NS404	5: Flat In-line	1	Range/stability		22.4	22.3	Table	450	28.13257906	21.21006529	-0.497131403	21.10512334	35.44454768	
SAW Data 2011-10-12 15:18:16.txt	NS404	6: Flat Perpendicular	1	Range/stability		22.3	22.4	Table	602	45.61572712	74.53225599	-18.58746589	76.8764771	29.88282696	
SAW Data 2011-10-12 15:55:23.txt	NS404	7: Horizontal Flipped	0.75	Range/stability		22.4	22.4	Table	216	27.75298042	1.66072321	-0.11006035	1.48234786	50.25758601	
SAW Data 2011-10-12 16:38:23.txt	NS404	7: Horizontal Flipped	0.25	Range/stability		22.3	21.9	Table	600	25.76162938	3.271088831	-0.03300172	3.25424883	41.01158697	
SAW Data 2011-10-12 17:14:16.txt	NS404	7: Horizontal Flipped	0.5	Range/stability		21.9	21.6	Table	315	22.99021656	2.150854591	-0.095557325	2.13928719	44.32104459	
SAW Data 2011-10-12 17:33:40.txt	NS404	7: Horizontal Flipped	0.25	Range/stability		21.8	21.5	Table	598	26.24640034	0.381399932	0.029142379	0.278447406	60.2019732	